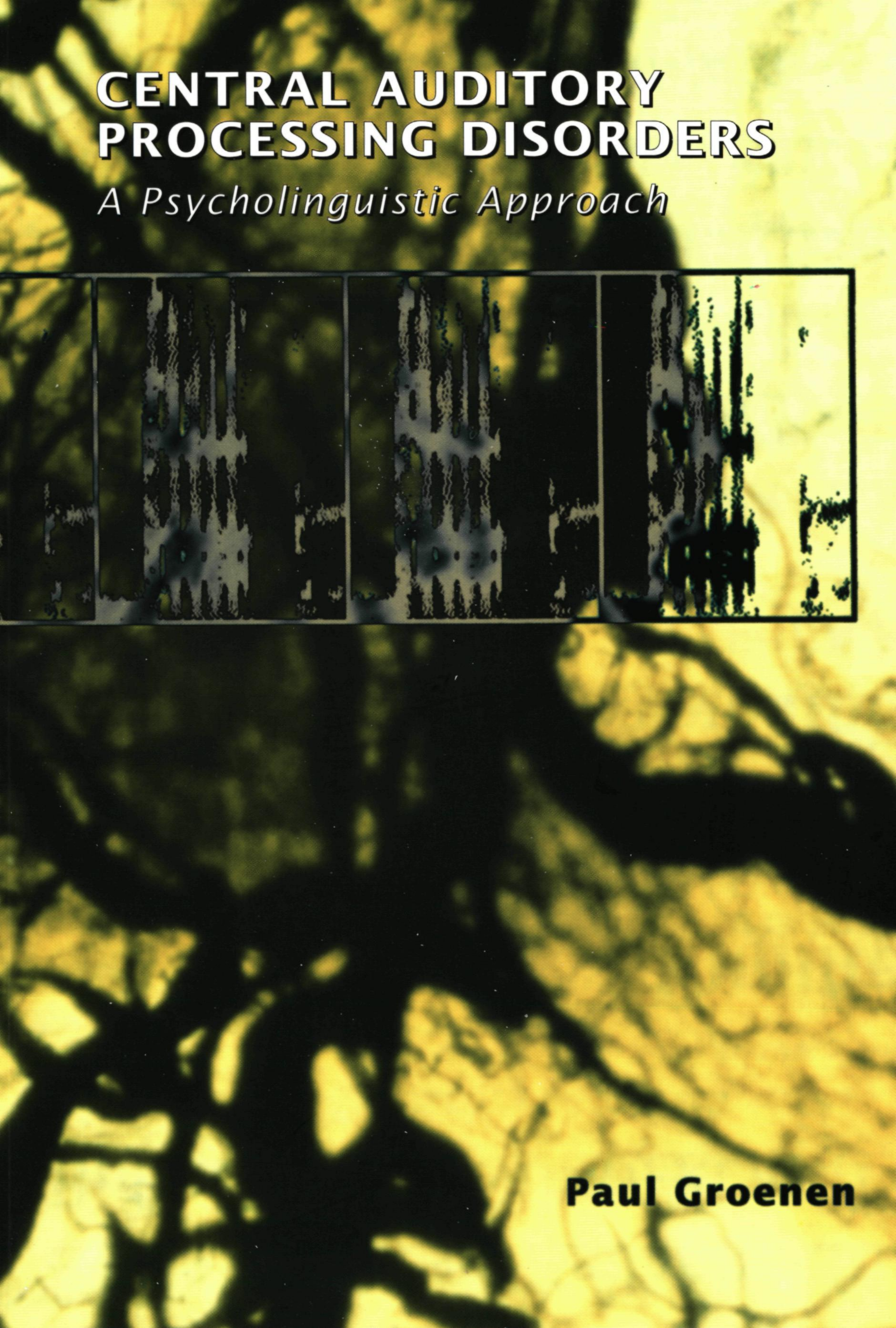
# CENTRAL AUDITORY PROCESSING DISORDERS

## *A Psycholinguistic Approach*



**Paul Groenen**

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# CENTRAL AUDITORY PROCESSING DISORDERS

*A Psycholinguistic Approach*

*Een wetenschappelijke proeve*
*op het gebied van de Medische Wetenschappen*

**PROEFSCHRIFT**

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To my parents

*Aan mijn ouders*

# INTRODUCTION: CENTRAL AUDITORY PROCESSING DISORDERS AND SPEECH INFORMATION PROCESSING

*Paul Groenen, Ben Maassen, Thom Crul*

Parts of this chapter appeared in **Groenen, P., Maassen, B., & Crul, Th. (1993). Psycholinguistische Aspekte zentraler Wahrnemungsstorungen: Die Auditive und Phonetische Phase** In P. Plath (Ed.), Zentrale Horstorungen (pp 110-122) Essen (Heidhausen): Geers-Stiftung; **Groenen, P., Maassen, B., & Crul, Th. (1994). Psycholingwistyczne aspekty centralnych zaburzen percepcji: Faza audytywna i fonetyczna.** Sluch, 2(7), 1 5; **Groenen, P., Maassen, B., Crul, Th., & Thoonen, G. (1996). The specific relation between place perception and place production in developmental apraxia of speech. In Th. W. Powell (Ed ),** Pathologies of Speech and Language: Contributions of Clinical Phonetics and Linguistics (pp 267-272), New Orleans, LA ICPLA, **Groenen, P., Maassen, B., & Crul, Th. (1996). Centraal auditieve stoornissen. Psycholinguistiek versus psychofysica. In M. Hoefnagel et al. (Eds.),** Taal, communicatie, gehoor (pp 187-199) Amsterdam WAP-Publicaties

## Abstract

Central auditory processing disorders concern decoding strategies of complex sound patterns in the absence of peripheral hearing loss Classical tests do not account for the structure and the complexity of the speech signal and do not take into account the complexity of processes involved in speech perception Therefore, classical psychophysically oriented tests lack a psycholinguistic basis We advocate to take the complex structure of the speech signal as well as the complex structure of the speech perception system as the starting-points in assessing central auditory processing disorders A psycholinguistic reduction of the redundancy of the speech signal (i e , the degradation of specific phonetic cues) could give supplemental information about central auditory processing disorders

# Central auditory processing disorders

A Central Auditory Processing Disorder (CAPD) can be defined as a disorder in the process of decoding sound patterns that cannot be explained by peripheral hearing loss The American Speech Language Hearing Association Task Force on Central Auditory Processing (ASHA, 1995) has suggested that central auditory function involves mechanisms and processes responsible for a) sound localization and lateralization, b) auditory discrimination, c) auditory pattern recognition, d) temporal aspects of audition, e) auditory performance decrements with competing acoustic signals, and f) auditory performance decrements with degraded acoustic signals

Central auditory processing disorders are not a unitary diagnostic syndrome From a behavioral point of view, subjects with CAPD are often characterized as poor listeners, easily distractable, showing short attention spans, and demonstrating poor memory for auditory information In this characterization, there is a large overlap with attention deficit disorder with hyperactivity, and less definite diagnostic categories such as concentration, attention, memory problems, and learning disorders Especially during childhood, CAPD may influence the development of aspects of language, including primary linguistic functions such as speech articulation, but also secondary linguistic functions such as reading, writing and spelling (Bellis, 1996)

Several tests and procedures are available for the assessment of central auditory functions For the diagnosis of CAPD, from an otological, neurological, and functional perspective, a comprehensive test battery is required (Musiek & Lamb, 1994, Willeford, 1985). The American Speech Language-Hearing Association (1990) made a division of tests into behavioral and physiologic measures Within the category of behavioral measures, monotic (e g , filtered speech, time altered speech, pattern recognition, ipsilateral competing signals, speech in noise), dichotic (e g , digits, syllables, words and sentences), and binaural (e g., fusion, selective listening, and rapidly alternating speech, masking level differences) tasks were distinguished Within the category of physiological measures, acoustic reflexes, and auditory evoked potentials were distinguished Musiek and Lamb (1994) mentioned the current lack of standardization of central auditory tests and procedures

In physiological terms, stages in auditory perception reflect the components of the auditory system, such as the cochlea, cochlear nucleus, trapezoidal body, superior olivary complex, inferior colliculus, and many cortical components Disorders in central auditory processing of speech are primarily associated with activity in the cortical areas A physiological approach, therefore, does not seem to be very specific in explaining the nature of speech perception problems

Unlike in physiology and psychophysiology, it is common convention in the art of psycholinguistics to draw boxes and arrows to visualize processes involved in speech perception This way of handling complex structures is, as Brown (1973) said, 'an odd interest, dependent, [we] suspect, on some rather kinky gene which, fortunately for our species, is not very widely distributed in the population " We agree, however, with Cutting and Pisoni (1978), that fruitful insights and testable hypothesis often emerge from such ventures

We would like to introduce a new approach, an approach which is based on psy cholinguistic aspects of speech and speech processing as opposed to psychophysical aspects of speech and speech processing.

In this thesis, there are two major questions 1) Do disorders of speech perception exist in a number of groups of subjects differing in pathological background?, and 2) Does a psycholinguistic approach to central auditory processing disorders yield new insights and knowledge about the type of the disorder?

The basic hypothesis is that a psycholinguistic approach is beneficial in assessing auditory processing disorders of speech The central idea is that speech perception problems should be assessed with strong reference to their psycholinguistic merit.

## Speech is coded: Psychophysical versus psycholinguistic reduction of redundancy

Speech sounds are characterized by a rather redundant acoustic organization Presentation of normal speech to assess CAPD, therefore, would yield an insensitive test The idea behind tests for assessing CAPD is to aggravate perception conditions as to gain easier access to malfunctioning central auditory processes Following Bocca and Callearo (1963), the argument is that, in a normal listener, both the neurological auditory system and the incoming acoustic speech signal are redundant In the context of high *extrinsic* redundancy of the acoustic speech signal, a slightly reduced *intrinsic* redundancy of the speech perception system can not be demonstrated. Therefore, one must present the subject with less redundant stimuli, in order to make the test procedure more sensitive

Several techniques have been applied to make tasks more difficult for the subject For instance, dichotic and diotic tests put demands on the competition or cooperation of the right and left ear, and speech in noise tasks complicate speech perception by embedding the speech signal in a background of noise. In general, clinical tests for assessing CAPD focus on aggravating speech conditions by adding sound (e g , noise in speech-in-noise tasks), subtracting information (e g , specific spectral energy in filtered speech tasks, or reducing intensity), or partitioning information (e.g., in binaural fusion tasks)

This type of reduction of the redundancy of the speech signal can be considered to be psychophysical in nature It concerns psychophysical dimensions which have no direct relation to the structure of the speech signal nor a direct relation to the multi-layered character of the speech perception system Psychophysically oriented tests for CAPD, therefore, lack a psycholinguistic base.

In normal conversation, the speech rate is approximately 12 to 15 phonemes per second Adequate speech perception, therefore, requires a high processing velocity It is important to understand not only the complexity of the speech perception system, but also the complexity of the the speech signal itself

For speech production, we are dependent on a rather inert system of articulators (jaw, lips, tongue, vocal folds) Estimates are that the rate of velocity for each articulator is 7 movements per second at maximum As mentioned earlier, the speech rate in normal conversation is 12 to 15 phonemes per second, which is 2 to 3 times as fast as the movements of the individual articulators The only way speakers can reach these high rates is by allowing for overlap of articulatory gestu res resulting in coarticulated segments The result of coarticulation is that, becau se of contextual influences, speech sounds rarely have physically uniform characte ristics Liberman (1996) mentioned this and referred to it as the encodedness of speech sounds

> *the sounds of speech are a special and especially efficient code on the phonemic structure of language, not a cipher or alphabet We use the term code, in contrast to cipher or alphabet, to indicate that speech sounds repre sent a very considerable restructuring of the phoneme message The acoustic cues for successive phonemes are intermixed in the sound stream to such an extent that definable segments of sound do not correspond to segments at the phoneme level Moreover, the same phoneme is most com-monly represented in different phonemic environments by sounds that are vastly different There is, in short, a marked lack of correspondence between sound and perceived phoneme This is a central fact of speech per ception It is, we think, the result of a complex encoding that makes the sounds of speech especially efficients as vehicles for the transmission of pho nemic information (Liberman, 1996)*

Psycholinguistic reduction, as compared to psychophysical reduction, of the redun dancy of speech bears on the fundamental characteristic of speech, i e , its enco dedness " We can use the encodedness of speech as the starting point to reduce the redundancy of speech sounds, i e to phonetically degrade speech sounds This will aggravate perceptual conditions and make perception more difficult for the subject Phonetic degradation is obtained by manipulating in the acoustic signal of a speech sound one of the critical cues which brings about its specific perception This type of reduction of the redundancy refers to the intrinsic coded character of the speech signal

## Speech information processing

To involve in profitable social communication, the proces of speech perception needs to function correctly The early stages of speech perception have to deal with a huge amount of time varying acoustic information entering the ear Central auditory integrity depends on the efficient and adequate functioning of several stages of speech coding processes

A number of speech perception models have been proposed Some models em phasize the implicit knowledge of the mapping between articulation and sound, e g , the Motor Theory of Speech Perception (Liberman, 1996) Others recognize the significance of interactions between features in speech perception, e g the Fuzzy Logical Model of Speech Perception (Massaro, 1990) This model proposes that acoustic cues are perceived independently from one another, are integrated and matched against a prototype Then again, the WRAPSA model (Word Recognition and Phonetic Structure Acquisition) of Jusczyk (1993) assumes preliminary auditory analysis that reflects the inherent organization of the human auditory system After the development of a weighting scheme, language specific phonetic decisions can be made

For the moment, it may be useful to characterize the early stages of speech perception according to the model of Cutting and Pisoni (1978) In Figure 1 1, an overview is given of these stages In this model, it is suggested that the process of speech perception constitutes a series of subprocesses, including a preliminary auditory analysis, further auditory and phonetic feature analysis, and the combination of phonetic features into a phonemic representation At any stage in the process of speech perception, information can be placed in short term memory The output of these early processes forms the input of higher order syntactic lexical and semantic analyses

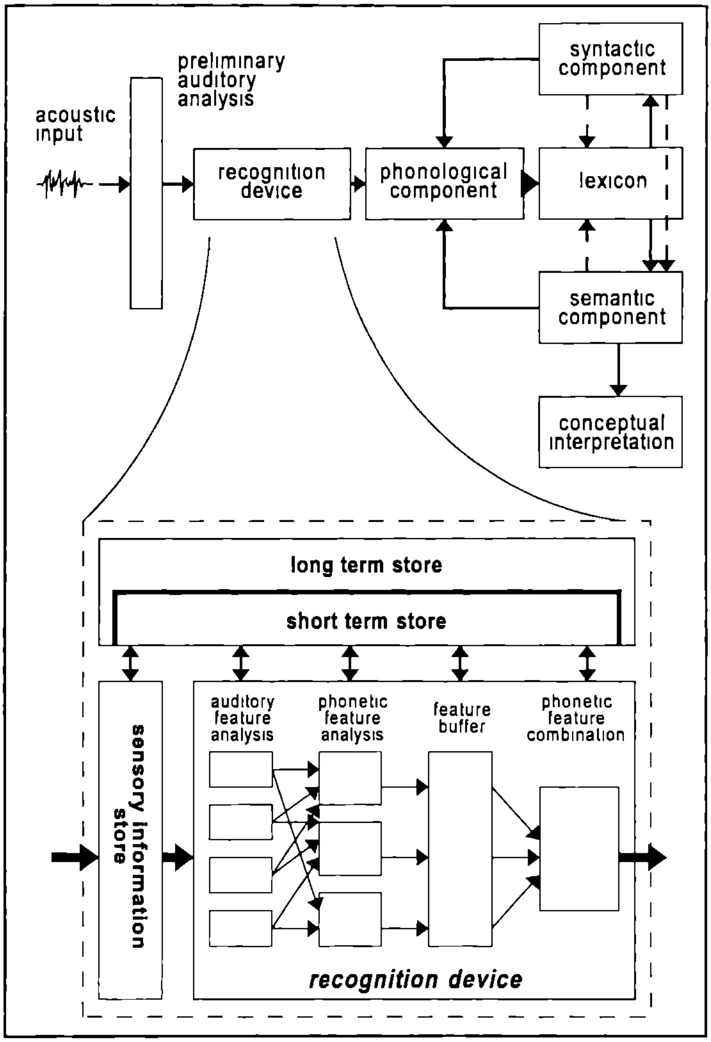



*FIGURE 1 1 Functional organization of the speech perception system (after Cutting & Pisoni 1978)*

The model of Cutting and Pisoni (1978) makes a clear distinction between auditory processing and phonetic processing In the auditory stage auditory features of the incoming signal are detected Stevens (1975) suggested a rather arbitrary list of what these features might include presence/absence of rapid change in the spectrum direction, extent, and duration of change within a portion of the spectrum, frequency range, duration, and intensity of noise, and relative onset of periodic and aperiodic portions of the signal Auditory processing includes a preliminary analysis and is related to auditory short term memory (Baddeley, 1992)

In the phonetic stage, auditory features are mapped onto phonetic features and assembled to a phonetic string Phonetic processing includes phonemic labeling strategies and is related to phonetic memory (Baddeley, 1992) It is here where the neural signal becomes language

For relevant literature on auditory and phonetic perception of speech, we refer to Cutting and Pisoni (1978), Elliott and Hammer (1988), Nittrouer and Studdert Kennedy (1987), Sussman and Carney (1989), and Sussman (1993a, 1993b)

In summary, (a) adequate perception involves multiple processing stages, and (b) the speech signal is highly variable because of coarticulatory influences When speech perception conditions are aggravated or parts of the perception system function poorly, central auditory processing disorders may arise In this thesis, auditory and phonetic processing in groups of subjects differing in pathological background will play a central role We will make use of a psycholinguistic reduction of the redundancy of the speech materials to assess auditory and phonetic processing The type of psycholinguistic reduction of the redundancy that we will apply is best understood within the paradigm of categorical perception

## Categorical perception

Categorical perception is a nonlinear mode of perceiving speech sounds The central idea behind the paradigm is that only those physical differences are recognized which have psycholinguistic relevance for functioning in a language environment This logic emphasizes the natural role of categorization and classification of percepts in speech perception

Knowledge about categories is likely to be retrieved by using speech materials in which category boundaries can be expected Therefore, the material to explore speech categories and category boundaries is a *speech continuum* This is a series of speech sounds in which one acoustic speech feature gradually, in discrete steps, changes from one phoneme to another phoneme, covering a phonological contrast In other words a critical cue which brings about the specific perception is manipulated The speech signal is phonetically degraded Note that this kind of manipulation is typical for a psycholinguistic reduction of the redundancy of the speech signal

Additional psycholinguistic relevance can be enforced by choosing contrasts on dimensions typical of speech perception and production Firstly, there is a distinction in the perception of vowels and consonants Isolated vowels are characterised by steady state entities, i e , the formants Within the category of consonants, three important dimensions may be considered (a) voicing (e g the contrasts /b/ /p/, /d/ /t/) (b) place of articulation (e g , the contrasts /b/ /d/, /p/ /t/), and (c) manner of articulation (e g , the contrasts /b/ /m/, /d/ /n/)

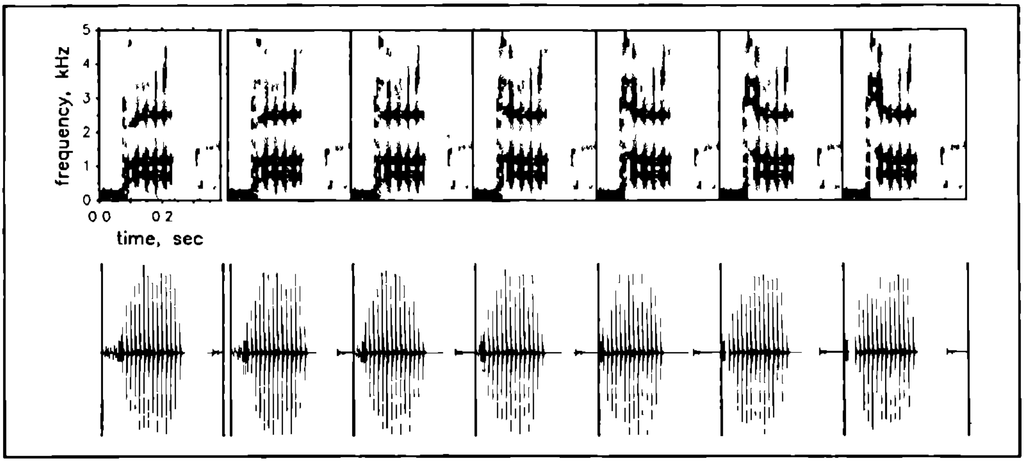



*FIGURE 1 2*
*Top rows Spectrograms of each of the elements of a place of articulation continuum /bɑk/ /dɑk/ Bottom rows Oscillograms of the elements of a voicing continuum /bɑk/ /pɑk/*

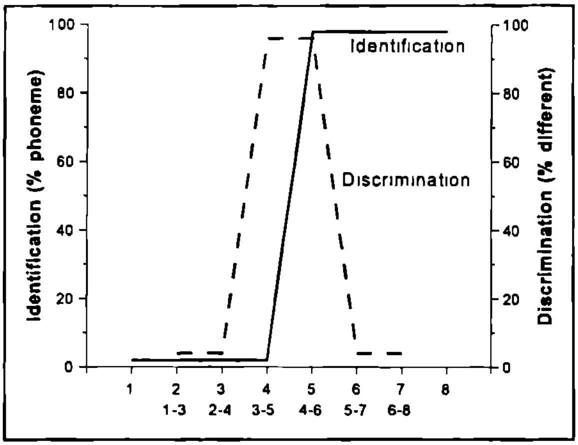


In Figure 1 2, examples are presented of speech continua for place of articulation (seven stimuli) and voicing (seven stimuli) The place of articulation continuum is determined by the slope of the second and third formant transitions Notice the gradual change in formant transition In /bɑk/ they rise, whereas, in /dɑk/ they fall The major acoustic cue carrying voicing information in Dutch initial stop consonants is voice onset-time (VOT), i e the time between laryngeal pulsing and opening of the mouth In /bɑk/ there is voice lead (voice onset before opening of te mouth), whereas in /pɑk/ there is voice lag (voice onset after opening of the mouth)

In our research, speech continua provide the base for two experimental tasks identification and discrimination In Figure 1 3, perceptual functions of identification and discrimination are presented With regard to identification, if the set of stimuli of this continuum is presented repeatedly in random order, the listener is likely to hear stimulus 1 through 3 as belonging to one category (e g , /b/), and stimulus 5 through 7 as belonging to the other category (e g , /d/) Normal listeners exhibit a steep identification curve, the change from /bɑk/ to /dɑk/ is abrupt The 50%-turnover point is called the phoneme boundary When the items are presented for discrimation, subjects will find it extremely difficult, if at all, to tell the difference between stimulus 1 and 3 or between stimulus 5 and 7, whereas they will have no problem in discriminating stimulus 3 from stimulus 5 Keep in mind that the physical difference between the elements of a pair are the same across pairs Only pairs that lie on opposite sides of the phoneme boundary are discriminated, if the stimuli of a pair lie within the same phoneme category, no difference is perceived

These are the ideal curves of categorical perception (See Liberman, Harris, Hoffman, & Griffith, 1957, and Studdert Kennedy, Liberman, Harris, & Cooper, 1970 for the early studies on categorical perception )

*FIGURE 1 3*
*Ideal manifestations of categorical speech perception The first row of labels under the X axis represent the numbers of the consecutive elements of the speech continuum used for the identification task The second row of labels under the X axis represent the numbers of the elements that constitute a pair of speech tokens of the continuum used for the discrimination task*




Information with respect to a specific psycholinguistic cue in stimuli that lie close to the phoneme boundary is less redundant than information in stimuli at more extreme positions of the continuum CAPD manifest themselves in more shallow identification curves (indicating less sharp category boundaries) and boundary shifts For discrimination, lower overall levels of discrimination or less sharp peaking may reflect CAPD

Identification and discrimation can be associated with specific stages in the speech perception system An identification task requires a phonemic judgment, and thus decisions are based primarily on the phonetic properties and features represented in phonetic short-term memory The decisions involved in a discrimination task may be based on information from both phonetic and auditory memory (Pisoni, 1973, Pisoni & Sawusch, 1975) Not only phonetic information is used but the listener can also base perceptual judgments of same and different on auditory speech properties stored in auditory short term memory

## Experimental groups

The role of speech perception in language disabilities has been a domain of controversy for many years Tallal (1978) and Duchan and Katz (1983) mention that there is mounting evidence that subjects with language disabilities have specific auditory processing impairments that may underlie their language dysfunction Especially during childhood, central auditory processing disorders may influence the development of various aspects of language, including primary linguistic functions such as speech perception and speech articulation, but also secondary linguistic functions such as reading, writing and spelling

In our opinion, all subjects who demonstrate language or language related problems are suspect for having CAPD of speech These subjects may suffer from delayed speech or language development, language learning disabilities, attention deficit disorders, phonological and articulatory disorders, apraxia of speech, dys lexia, and specific language impairment In addition, subjects whose language acquisition has been disrupted by exogeneous factors are suspect for CAPD These subjects may suffer from an acquired language dysfunction severe history of otitis media with effusion, aphasia, closed head injury, hemisphere and posterior tempo ral lobe lesions, and a history of long term sound deprivation in congenitally, pre-lingually, and postlingually deaf cochlear implant users.



## Structure of the thesis

In Chapters 2 to 7, six studies on the perceptual behavior of different groups of subjects are presented These studies focus on the perceptual skills associated with specific pathologies Each chapter will tell its own specific story, represents a study that stands on its own, and can be read as such There is, however, a progressive development in methodology and theoretical reflection on central auditory processing disorders

### Chapter 2

In Chapter 2, auditory and phonetic perception of voicing and place of articulation in children with developmental dyslexia is examined Developmental dyslexia is a condition manifested by difficulties in learning to read and write If the internal representations of speech sounds are weak, problems in reading and spelling may arise Speech perception of a group of children with developmental dyslexia and two control groups of children (age matched and matched on reading level) are studied To determine the clinical value of the perceptual tasks, perception ability is related to reading and spelling ability The main question is, does support exist for a functional relation between speech perception and reading and spelling in deve lopmental dyslexia?

### Chapter 3

In Chapter 3, identification of brief auditory spectral cues concerning the feature place-of-articulation is studied in children with articulation problems Firstly, identification functions with decreasing formant transition durations are investigated Then, identification tasks based on stimuli with variable formant transition durations are administered to groups of misarticulating children and adolescents, and two control groups (children and adults) The clinical value of formant transition duration is assessed and the causal link between perception and production is dis cussed.

### Chapter 4

In Chapter 4, a study on the perception of major and minor voicing cues in children with a severe history of otitis media with and without language impairment is exa mined Research on the relationship between early otitis media with effusion, language impairment, and central auditory processing has been equivocal

Identification and discrimination of initial bilabial stop consonants differing in voicing by children with a history of severe OME is studied The groups studied are controlled for language impairment. We made use of one major voicng cue voice onset time, and four minor cues (a) the length of the noise burst; (b) the intensity of the noise burst; (c) the formant transition duration of F1, F2, and F3; and (d) the range of the frequency shift of F1 The ability of these children to perceive major and minor voicing cues is examined



**Chapter 5**

In Chapter 5, the specific relation between perception and production of place-of-articulation features in developmental apraxia of speech is studied Developmental apraxia of speech is a disorder of phonological and articulatory output processes. However, it has been suggested that perceptual deficits may contribute to the disorder Children with developmental apraxia of speech and control children are administered tests of identification and discrimination of resynthesized and synthesized monosyllabic words differing in place of-articulation of the initial voiced stop consonants Measures of speech perception are compared to measures of speech production Of special interest is the clinical value of the perceptual tasks

**Chapter 6**

In Chapter 6, auditory and phonetic perception of vowels in children with apraxic speech disorders is investigated. Auditory and phonetic processing of vowels in the etiology and maintenance of apraxic speech disorders is poorly understood. Stimulus specifications are chosen as to eliminate perceptual redundancy by moving the formants to a "neutral vowel position." Differences between the utility of vowels and consonants in the assessment of CAPD are discussed. Interindividual variation is measured and it is studied if subgroups with similar atypical perception patterns can be established In addition, the differential and clinical value of perception measures is assessed

**Chapter 7**

In Chapter 7, auditory processing of cochlear implant subjects is studied using electrophysiological techniques Processing in the auditory cortex may play a role in the unexplained variability in cochlear implant benefit. P300 and N1/P2 are elicited in postlingually deaf cochlear implant users wearing a Nucleus multichannel cochlear implant Four sound contrasts are presented: (a) pure tones; (b) place-of-articulation; (c) voicing, and (d) vowels. The material consists of manipulated synthesized stimuli which, in previous studies, have proven to sensitively assess central auditory functions. P300 results of the cochlear implant users are compared to behavioral results of speech perception ability

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Chapter 2

# IDENTIFICATION AND DISCRIMINATION OF VOICING AND PLACE-OF-ARTICULATION IN DEVELOPMENTAL DYSLEXIA

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## Abstract

Developmental dyslexia is a disorder manifested by difficulties in learning to read and write. If the internal representations of speech sounds are weak, problems in reading and spelling may arise Identification and discrimination of the features voicing and place-of-articulation of a group of children with developmental dyslexia and two control groups of children (age-matched and matched on reading level) were studied. To determine the clinical value of the perceptual tasks, perception ability was related to reading and spelling ability Children with developmental dyslexia demonstrated consistent identification for place-of-articulation. Identification differences between groups for voicing could be attributed to reading-level and not to qualitative functional differences between dyslexic and nondyslexic groups For the perception of both voicing and place-of-articulation, children with developmental dyslexia demonstrated poorer discrimination than the age-matched and reading level-matched control children. Significant negative correlations between performance on the perception tasks and reading and spelling ability provided additional support for a functional relation between speech perception and reading and spelling in developmental dyslexia The data support the suggestion that perceptual problems may underlie developmental dyslexia

## Introduction

The process of reading and writing demands the integration of skills which are specific to the process of written language with skills developed for the perception and production of speech Developmental dyslexia is a disorder manifested by difficulties in learning to read and write despite conventional instruction, adequate intelligence and sociocultural opportunity (Critchley, 1975) It has been associated with deficits in central auditory function deficits in phonologic short term memory, and specific language impairments (Steffens, Eilers, Gross Glenn, & Jallad 1992 Tallal, 1980) There is growing evidence that lower level speech perception disabilities may underly language impairment in children (Groenen, Crul, Maassen, & Van Bon, 1996 Groenen, Maassen, Crul, & Thoonen, 1996, Tallal & Stark, 1980) Bradley and Bryant (1983) stated that making young children aware of the sounds of their language will help them in learning to read and write Mattingly (1972) mentioned that it is reasonable to assume that the process of learning to read serves as the occasion for children to become consciously aware of linguistic units in speech The aim of this study is to determine the quality of internal representations of speech sounds in children with developmental dyslexia The hypothesis is that problems with speech processing make part of reading and writing problems

Reed (1989) mentioned several processing deficits underlying reading disability One of the approaches addressed the possibility of inadequate phonological representations Poor readers may be less aware of the phonological structure of words than are good readers Reading disabled children may not have mastered the rules relating the phonology to the spelling system Phonological and phonetic representations in adult and child dyslexia have been addressed in a number of studies Brandt and Rosen (1980) failed to demonstrate speech perception problems in children with dyslexia Children with reading impairments labeled and discriminated speech sounds much like normal reading children and adults Lieberman Meskill, Chatillon, and Schupack (1985), however, demonstrated that adult subjects with dyslexia show deficits in the identification of vowels and the feature place of articulation in consonants Steffens et al (1992) found that the overall performance in identification and discrimination by adults with dyslexia was generally less accurate Godfrey, Syrdal Lasky, Millay and Knox (1981) investigated the perception of place of articulation in children with dyslexia They concluded that the pattern of identification and discrimination differences between dyslexic and control children suggested an inconsistency in the dyslexics phonetic classification of auditory cues In the present study, the quality of internal representations of speech sounds in children with developmental dyslexia is studied on a identification and a discrimination level

The importance of speech processing abilities for the development of language has been studied in children with normally developing language (e g , Nittrouer & Studdert Kennedy 1987 Sussman & Carney 1989 Sussman, 1993a) and in children with language impairments (e g Elliott & Hammer 1988, Sussman, 1993b) In the present study, both identification and discrimination was studied in children with developmental dyslexia Identification and discrimination address speech perception and tap into the integrity of linguistics units

Language delayed children seem to benefit from redundancy in the acoustic signal (Tallal & Stark, 1980) Brady, Shankweiler, and Mann (1983) suggested that poor readers require more complete auditory stimulus information than good readers in order to apprehend the phonetic shape of words Degraded speech stimuli with a reduced redundancy, therefore, could prove to have differential value and to be a sensitive means for assessing perceptual problems in developmental dyslexia In the present study, the speech signal was degraded by means of speech sound continua. A speech continuum consists of a series of speech tokens that vary acoustically for a single phonological contrast A speech sound continuum contains words of varying phonemic ambiguity. The endpoint tokens are most representative with regard to phonemic clarity The intermediate tokens vary in phonemic clarity and as such can be interpreted as reflecting a certain level of stimulus degradation By using speech sound continua containing degraded speech tokens, a sensitive test for the perception of speech was developed.

There is evidence that poor internal representations of speech sounds reflect problems in processing brief acoustic cues (Tallal, 1980, Reed, 1989). In Tallal (1980), these brief acoustic cues basically concerned formant transitions Reed (1989) mentioned the importance to understand the generality of dyslexia, it may affect only certain types of speech sounds To address more than one type of speech sound, in the present study the perception of formant transitions as well as voicing cues in children with developmental dyslexia was investigated As a cue in the domain of formant transitions, place of-articulation was studied, whereas, as a cue in the voicing domain, voice onset time studied A major issue in studies on the relation between speech perception and dyslexia is the nature of perception problems Both Brandt and Rosen (1980) and Godfrey et al. (1981) used control groups matched on the basis of chronological age It could not be determined whether the group differences in speech perception were developmental or deviant in nature Thus, in Brandt and Rosen (1980) and Godfrey et al. (1981), the lack of a reading level-matched control group made it impossible to determine whether the observed differences in perception were caused by developmental differences in reading level or by functional differences in perception. Ziegler, Tallal, and Curtiss (1990) and Schmitt and Meline (1990) emphasized the need for appropriate variables on which to match groups One of the suggestions made by Watson and Willows (1995) concerned the employment of a reading-level match instead of the traditional chronological-age match when studying children with learning disabilities who have general reading problems. Vellutino and Scanlon (1989) acknowledged the importance of a reading-level match design, but also warned for the risks in drawing conclusions via this methodology They mentioned that the 'general concern is the ambiguity inherent in interpreting results comparing chronological age and reading level matched groups on cognitive tasks that could be affected by reading disability" Manis, Szeszulski, Holt and Graves (1990) proposed to use both designs in developmental research, until problems of chronological-age and reading-level control designs are resolved In the present study, both control measures were used, the children with dyslexia were compared to a control group matched on chronological age, and a younger control group matched on reading-level.

The present study was aimed at determining if poor internal representations of speech sounds underly developmental dyslexia in children To determine the clinical value of the perceptual tasks, perception ability was related to reading and spelling level Summarizing, our study extended previous research in combining: (a) using identification and discrimination tasks; (b) using sensitive measurement materials and procedures (speech continua), (c) testing two general dimensions (spectral cues place-of-articulation, and temporal cues voicing), and (d) using two control measures by comparing dyslexics to control groups matched both on chronological age and reading-level



## Method

### *Subjects*

The subjects with developmental dyslexia were eight children (five boys and three girls, mean age 105.4 months) of which four children attended schools specialized in the remediation of learning disabilities and four children attended regular elementary schools. All schools were in the south and east of the Netherlands within 40 kilometers from the city Nijmegen. In the pre-selection, information was obtained from medical and educational records Inclusion and exlusion criteria were used with reference to suggestions made by Ziegler et al (1990).
The criteria for inclusion were:

1 Diagnosis of developmental dyslexia according to the pedagogue for special education.
2 Confirmed heredity of dyslexia There were multiple cases of dyslexia in the family
3 Problems in reading and spelling. The reading level was assessed with the one-minute test for speed-reading of words of Brus and Voeten (1973) and the AVI reading test for sentences of Van den Berg and te Lintelo (1977). The spelling level was assessed with dictation tests for words of In den Kleef (1988) and Geerling and Geurts (1986) and the Van der Wissel (1963) spelling test for sentences. Scores were expressed in educational age-equivalent. Subtraction of the educational age-equivalent in months from the educational age (10 months per school year) yielded the educational delay. For all tests an educational delay of at least six months was required.
4 Normal intelligence, as measured by the WISC-R intelligence test (Wechsler Intelligence Scale for Children, 1986). Performance IQ above 90 was required.
5 Significantly lower verbal than performance IQ on the WISC-R intelligence test.

In Table 2 1, the mean scores for the children with dyslexia on the tests are presented In addition, information derived from the medical and educational records was used to determine exclusion criteria. This information indicated that each selected child (a) had no structural organic problems, (b) did not have otorhinolaryngologic problems, and (c) did not suffer from severe attention deficits, as tested with the Bourdon-Vos test for auditory attention (Vos, 1992).

TABLE 2 1
Descriptive statistics for the dyslexic group

| | M | SD | Range |
|---|---|---|---|
| Age (months) | 105 4 | 9 [illegible] | 91 119 |
| **WISC R** | | | |
| Verbal IQ | 94 7 | 7 7 | 87 110 |
| Performance IQ | 113 8 | 22 5 | 90 158 |
| Performance Verbal | 21 0 | 13 7 | 10 48 |
| **Reading (educational delay in months)** | | | |
| Words | 16 5 | 7 0 | 6 24 |
| Sentences | 16 5 | 7 0 | 6 24 |
| **Spelling (educational delay in months)** | | | |
| Words | 13 2 | 4 8 | 6 24 |
| Sentences | 13 2 | 4 8 | 6 18 |

**Note**
The reading level was assessed with the One minute test for words of Brus and Voeten (1973) and the AVI test for sentences of Van den Berg and te Lintelo (1977) The spelling level was assessed with tests for words of In den Kleef (1988) and Geerling and Geurts (1986) and a test for sentences of Van der Wissel (1963)

There were two control groups One was matched on chronological age and the other was matched on reading level The age matched group of control subjects were 12 children (mean age 105 months range 91 to 121 months) attending a regular elementary school The group matched on reading level consisted of eight subjects Each subject was matched on reading level with a subject with dyslexia on the assessed educational age equivalent The mean reading delay across subjects with dyslexia was 16 5 months (SD=6 8) The mean age for the subjects with dyslexia was 105 4 months (range 91 to 119 months) The mean age for the control group matched on reading level was 84 months (range 75 to 98 months)

The children of both control groups were selected by their teachers The teachers were instructed to select moderately achieving children who were not outstanding with regard to social classroom behavior and cooperativeness The children showed no evidence of learning disabilities a history of hearing problems speech and language problems or speech limiting structural abnormalities Based on school performance and information from the classroom teachers normal levels of cognitive motoric and perceptual functioning could be assumed

The children in both the experimental and the control groups met the following selection criteria (a) absence of hearing loss on bilateral pure tone audiometric testing with air conduction thresholds at 250 500 1000 2000 4000 Hz (ISO 1985) at the time of testing the maximally allowed hearing loss was 25 dB HL for either ear (b) no previous exposure to synthesized speech (c) Dutch as the native language and (d) no bilingualism In addition only children who could correctly identify

11 out of a series of 12 words consisting of six random repetitions of two speech tokens representing the perceptually clearest ends of the speech continua (i e., /bɑk/ and /dɑk/, or /bɑk/ and /pɑk/) were admitted to the study. All three end-point tokens were Dutch words. The probability of obtaining 11 correct responses out of 12 trials based on chance alone was .003 The subjects had to pass this pre test so that children who had difficulties accomodating to artificial speech could be exluded The pretest was administered prior to actual testing, and all of the children with developmental dyslexia and all the children in the control groups passed the pretest.



## Stimuli

The original stimulus signal for both the place-of-articulation and the voicing continuum was an adult male utterance of a single word /bɑk/ (the Dutch word for *box*). Both the place-of-articulation and the voicing continuum originated from this stimulus /bɑk/ After A/D conversion with a DASH-16 data-acquisition board (12 bit sampling at 10 kHz; band-pass filtering between 40 and 5000 Hz, low-pass cut-off frequency 5000 Hz with a decline of 60 dB/octave), the Interactive Laboratory System (ILS-PC, V6 1, 1989) was used to manipulate the spectral structure of the initial formant transitions Only the vocalic portion (formant transitions plus steady-state vowel) was analyzed with pitch-synchronous linear predictive coding (covariance method, pre-emphasis factor 98, Hamming window), which yielded 12 reflection coefficients (Markel & Gray, 1976). The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients to autoregressive coefficients and then performing a fast Fourier transformation (FFT) The result was smoothed spectrally by interactively adjusting the formant frequencies. F0 for all words was 104 Hz.

### *Place-of-articulation continuum*

The consecutive stimuli of the continuum ranged perceptually from /bɑk/ to /dɑk/ (i e , the Dutch word for *roof*) and differed from one another in the starting value and slope of the transitions of the second and third formant The onset frequencies of the F2 and F3 for each stimulus are shown in Table 2.2 F1 always started at 400 Hz The transition of the first formant was 20 ms in duration The transitions of the second and third formants were 52 ms in duration All transitions were linear The final 98 ms of the vowel consisted of steady-state formants appropriate for the Dutch vowel /ɑ/ with center frequencies at 750 Hz (F1), 1150 Hz (F2), and 2500 Hz (F3) The sampled data were resynthesized with a pitch-synchronous synthesis procedure by transforming the manipulated reflection coefficients to inverse filter coef ficients. Pitch period excitation used a unit pulse The resynthesized vowel parts were spliced back into the original utterance /bɑk/, which produced seven stimuli ranging from /bɑk/ to /dɑk/. The total length of each stimulus was 381 ms, con sisting of (a) voice-lead 71 ms, (b) burst 10 ms, (c) vowel /ɑ/ 150 ms, divided into 52 ms transition duration and 98 ms steady state, (d) silence interval (occlusion period /k/) 70 ms; and (e) release /k/ 80 ms.

TABLE 2 2

Onset frequencies (in Hz) for the second and third formant transitions of the stimuli of the place of articulation continuum

| Stimulus | F2 | F3 | |
|---|---|---|---|
| 1 | 1000 | 2150 | /bɑk/ |
| 2 | 1083 | 2317 | |
| 3 | 1167 | 2483 | |
| 4 | 1250 | 2650 | |
| 5 | 1333 | 2817 | |
| 6 | 1417 | 2983 | |
| 7 | 1500 | 3150 | /dɑk/ |



*Voicing continuum*

An 8-step /b-p/ continuum was generated The stimuli of the continuum ranged perceptually from /bɑk/ to /pɑk/ (i e , *package*) and differed from one another in Voice Onset Time (VOT) values of about 10 ms Voice lead was cut back in steps of about 10 ms Voice lag was implemented by inserting increasing silent intervals between the burst and the vocalic portion The consecutive eight stimuli had VOTs of 52 7, 40 9, 29 1, 19 1, 10 8, 0, +8 0, and +16 0 ms

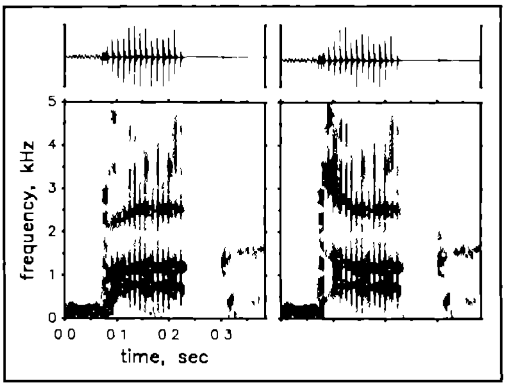



*FIGURE 2 1*
*Waveform and spectrogram of the place of articulation endpoint tokens /bɑk/ (left panel) and /dɑk/ (right panel)*

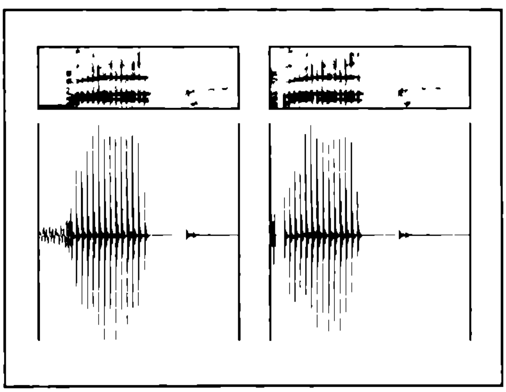


*FIGURE 2 2*
*Waveform and spectrogram of the voicing endpoint tokens /bɑk/ (left panel) and /pɑk/ (right panel)*

Stimulus phonemic quality was checked by having 10 adults label 10 repetitions of each of the stimuli of both continua presented in random order For individual subjects, the phoneme boundary was located between stimulus 3 and 5 on the place-of articulation continuum. The mean phoneme boundary for the voicing contrast occurred at a VOT of 11 31 ms. The shape of the identification function was representative for the Dutch language (Slis & Cohen, 1969) These results indicated a valid choice of frequencies in the spectral and temporal manipulations.

In Figure 2.1 and 2.2, waveforms and spectrograms displaying the endpoint tokens for the /bɑk/-/dɑk/ continuum and /bɑk/-/pɑk/ continuum are presented.



### *Procedure*

The stimuli were recorded and played back using an Ampex 467 DAT-tape on a Grundig Fine Arts Digital Audio Tape recorder (type DAT-9000: 16 bit D/A converter, 2-fold oversampling, sampling frequency 48 kHz). Presentation was via a Beyerdynamic closed headphone (Type DT770). The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL) Subjects were tested in a quiet room.

Each subject was examined once. In order to get accustomed to the artificial speech, the subject first listened to six repetitions of each of the four endpoint stimuli The subject then had to identify 11 out of a series of 12 endpoint stimuli correctly for both continua (see subject selection criteria). After this, the subject was administered the main experimental tasks: two identification and two discrimination tasks

The identification task was based on a two-alternative forced choice response procedure and consisted of 10 repetitions of each of the stimuli of the continuum presented in a random order in five series This resulted in five series of 14 stimuli for the place-of-articulation continuum and five series of 16 stimuli for the voicing continuum The stimuli were separated by an interstimulus interval of 5000 ms For the place-of articulation condition, the subjects could identify the stimulus by pointing to one of two pictures: a picture of a box, representing the stimulus /bɑk/, or a picture of a roof, representing the stimulus /dɑk/. For the voicing condition, the subjects could identify the stimulus by pointing to either a picture of a box, representing the stimulus /bɑk/, or a picture of a package, representing the stimulus /pɑk/.

The discrimination tasks consisted of same-different (AX) judgments In order to obtain a bias-free measure of discriminability, the discrimination tasks were set up in such a way that signal detection analysis could be applied (Coombs, Dawes, & Tversky, 1970). For this, each task contained physically different as well as identical pairs. In the place-of-articulation condition, subjects were presented three series of 15 stimulus pairs. Each series consisted of one identical pair for each of the seven stimuli, one physically different pair for each of the five possible 2 step comparisons (1-3, 2 4, 3-5, 4 6, 5 7), and one physically different pair for three 3-step comparisons (2-5, 3-6, 4-7). The 3-step comparisons were treated as dummies explicitly intended to elicit more "different" responses In the voicing condition, subjects were presented three series of 17 stimulus pairs Within each series, there was one identical pair for each of the eight stimuli, one physically different pair for each of the six 2-step comparisons (1-3, 2-4, 3 5, 4 6, 5 7, 6 8) and one physically different pair for three 3-step comparisons (2-5, 3 6, 4-7) In each series, the pairs were randomly ordered with an intrapair interstimulus interval of 600 ms and an interpair interval of 5000 ms An intrapair interstimulus interval value of 600 ms had proven to be a sensitive one in previous studies by Groenen, Maassen, et al (1996) and Groenen, Crul, et al (1996). To avoid difficulties with the verbal con cepts of "same" and "different", the subjects were required to point to one of two pictures after hearing a pair of stimuli: a picture of a triangle and a circle, representing the concept "different", or a picture of two circles, representing the concept "same".

Half of the subjects began with the place-of-articulation condition while the other half began with the voicing condition. The subjects always participated in the identification task before the discrimination task. The children were encouraged to respond but never received differential feedback for particular responses



## Results

### *Identification*

Each individual identification curve was submitted to probit transformations (Finney, 1971). The probit method determines the value of the phoneme boundary and slope by iteratively computing the cumulative normal distribution that comes closest to the data, using a maximum likelihood criterion. The resulting distribution has a mean (i e., the interpolated 50% crossover point or phoneme boundary) and a standard deviation (i e., a measure of the variability of scores around the mean). The slope is the reciprocal of the standard deviation and indicates the range of uncertainty in distinguishing one phoneme category from another. A high slope

**TABLE 2.3.**
Mean identification results for the children with developmental dyslexia and the control children on the place-of-articulation and voicing stimuli.

| | Phoneme boundary | Slope |
|---|---|---|
| **Place-of-articulation (stimulus number)** | | |
| Dyslexic | 3 75 | 2 68 |
| Age-matched control | 4 19 | 2 85 |
| Reading-level-matched control | 4 24 | 2 50 |
| **Voicing (voice onset time)** | | |
| Dyslexic | -10 42 | 0 117 |
| Age-matched control | -9 88 | 0 220 |
| Reading-level matched control | -9 60 | 0 114 |

**Note.**
Voice Onset Time is not evenly distributed along the x-axis. The consecutive stimulus intervals are approximately 10 ms in the voice-lead phase and 8 ms in the voice-lag phase

value indicates a small uncertainty range and suggests a highly consistent ability to categorize a speech contrast, whereas, a low slope value indicates a large range of uncertainty and suggests difficulties in identifying the speech stimuli

*FIGURE 2 3*
*Mean percentages 'D responses as a function of stimulus number of the place of articulation continuum for the children with developmental dyslexia and control children Vertical lines indicate the location of the mean phoneme boundary*

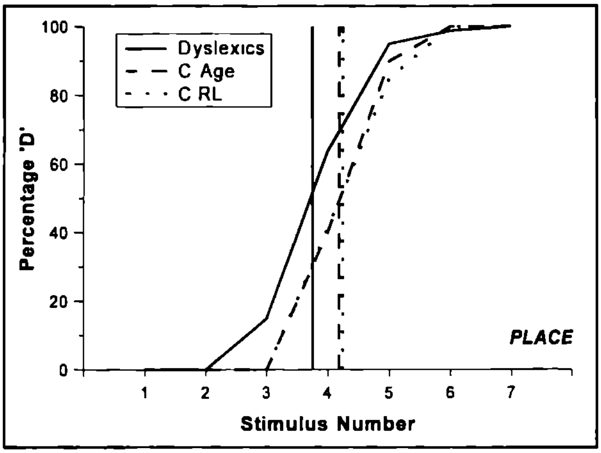
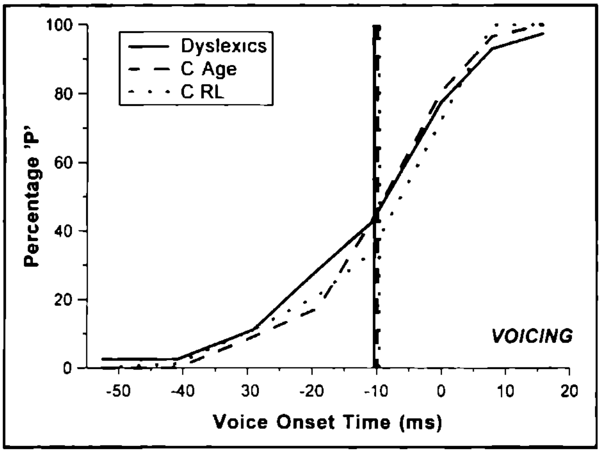



*FIGURE 2 4*
*Mean percentages 'P' responses as a function of Voice Onset Time (voicing continuum) for the children with developmental dyslexia and control children Vertical lines indicate the location of the mean phoneme boundary*




In Table 2 3, the mean phoneme boundary and slope scores for the developmental dyslexic and the control groups are presented for both the perception of place-of-articulation and voicing

*Place-of articulation*

In Figure 2 3, the mean identification curves for the children with developmental dyslexia and the control children for the stimuli differing in place-of-articulation are presented

A one way ANOVA was used to test for significant differences between means There were no significant differences in mean slope between the dyslexic and the control groups This indicates that the children with developmental dyslexia perfor med as consistently as the control children The mean phoneme boundary for the dyslexic group was shifted to the left compared to that of each control group This difference approached significance ($F$ (2)=2 93, $p$=0.072) [2]

*Voicing*

In Figure 2 4, the mean identification curves for the children with dyslexia and the control children for the stimuli differing in voicing are displayed A one way ANOVA (Subject Group) resulted in a significant effect on slope ($F(2)=4\ 94$, $p=\ 016$) A Tukey's studentized range test showed that the dyslexic group and the control group matched on reading level demonstrated lower slope values than the control group matched on age The dyslexic group and the control group matched on rea ding level were not different from each other This indicated that the children with developmental dyslexia and the children matched on reading level labelled less consistently than the control children matched on chronological age There were no significant differences in phoneme boundary

## *Discrimination*

The discrimination functions plot the discriminability of each 2 step pair in terms of a nonparametric estimate of d' ( ln eta, Wood, 1976) as a function of stimulus pair Discriminability equals zero when performance is at chance It increases with in creasing discrimination accuracy without influences of bias to respond "same" or "different' Discriminability is maximal at the ln eta value of 4 6, this value is obtained when the probabilities for the correct "difference" and correct "same" responses are both 99, the value assigned (for computational purposes) when the actual probabilities were 1 00

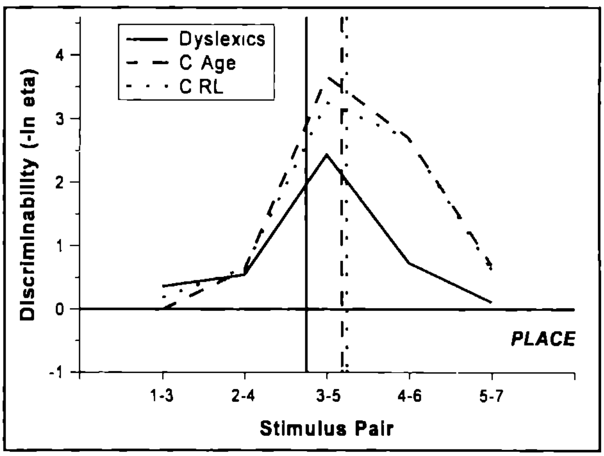



*FIGURE 2 5*
*Mean discrimination sco res as a function of sti mulus pair of the place of articulation continuum for the children with developmental dyslexia and control children Vertical lines indicate the location of the mean phoneme boundary*

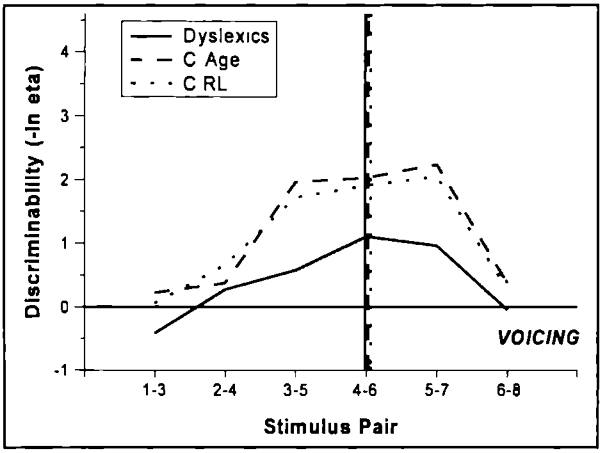
*Place-of articulation*

In Figure 2 5, the mean discriminability functions for the dyslexic and the control groups are presented A 2 way ANOVA (Subject Group x Stimulus Pair) with re peated measures on Stimulus Pair was performed There was a significant effect of Subject Group ($F(2,25)=5\ 13$, $p=\ 013$) A Tukey's studentized range test for the mean discriminability showed that the dyslexic group demonstrated a lower level of discrimination than both the control groups The control age matched control group and the control group matched on reading level were not different from each other

*Voicing*

In Figure 2 6 the mean discriminability functions for the children with dyslexia and the control children are displayed A 2 way ANOVA (Subject Group x Stimulus Pair) with repeated measures on Stimulus Pair was performed In accordance with the discrimination of place of articulation features, there was a significant effect of Subject Group ($F$ (2,25)=5 45, $p$= 011) A Tukey's studentized range test for the mean discriminability showed that the dyslexic group demonstrated a lower level of discrimination than both the control groups The age matched and reading level matched control groups were not different from each other

*FIGURE 2 6*
*Mean discrimination scores as a function of stimulus pair of the voicing continuum for the children with developmental dyslexia and control children Vertical lines indicate the location of the mean phoneme boundary*




## *Clinical value*

In order to determine the relation between perception ability on the one hand and reading and spelling ability on the other, the data of the subjects with dyslexia were used to cross correlate mean discriminability for voicing and place of articula tion with educational delay in (a) reading, (b) spelling, and (c) mean educational delay in reading and spelling (all scores were averaged across words and senten

**TABLE 2 4**
Pearson product moment correlation coefficients of the reading and spelling measures with the the mean discriminability for voicing and place of articulation

| | Reading | Spelling | Mean reading/ spelling |
|---|---|---|---|
| **Mean discriminability** | | | |
| Voicing | 76* | 76* | 82* |
| Place of articulation | 62(*) | 87** | 77* |

Note
The individual reading and spelling levels were computed by taking the mean educational delay in word and sentence performance **p< 01 *p< 05 (*)p< 1

ces) Pearson product moment correlation coefficients are represented in Table 2 4 If perception is related to reading and spelling (i e , high level of mean discrimina bility and low score in educational delay), then the correlations should be signifi cantly negative

The correlation coefficients for all comparisons were high and reached significance, except for the relation between reading ability and discrimination of place-of articulation (there was a trend, however). As an example, in Figure 2.7, the mean discriminability for place of-articulation and voicing is plotted against the mean educational delay in reading and spelling per subject The mean discriminability scores for place of-articulation and voicing were negatively related to the mean educational delay in reading and spelling ($r$=-.77, $p$= 024 and $r$=- 82, $p$=.013, respectively) The correlations revealed a firm relationship between discriminability of place-of articulation and voicing on the one hand and reading and spelling ability on the other

## Discussion

To answer the question whether children with developmental dyslexia have poorer internal representations of speech sounds, we have to distinguish between identifi cation and discrimination performance. With regard to identification, children with developmental dyslexia demonstrated slopes for place-of-articulation which were not significantly different from the age matched and reading level matched control children. For voicing, children with dyslexia showed a less steep identification curve than the age matched controls However, there was no difference in slope compared with the younger control group matched on reading level Identification differences between groups, therefore, could be attributed to developmental aspects associated with reading-level and not to qualitative functional differences between dyslexic and nondyslexic groups

Discrimination performance of children with developmental dyslexia and control children was reflected in discriminability differences. For the perception of both

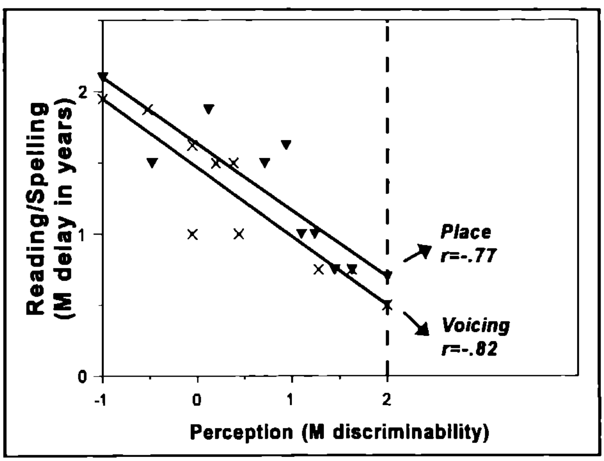



*FIGURE 2 7*
*Scatterplot of the mean discriminability and mean educational delay in reading and spelling per subject for the place of articulation and the voicing condition Regression lines are included for both condi tions*

voicing and place-of articulation, children with developmental dyslexia demonstrated poorer discrimination than the age-matched as well as the reading-level matched control children

The differences in the slope of the identification functions and the overall discrimination were modest, and the sample sizes were small The data seem to point in the direction of discrimination problems to be deviant instead of developmental in nature, whereas, problems in identification to be the result of a developmental delay. The clinical value of speech discrimination tasks was demonstrated by the relation between the mean discriminability data and the reading and spelling data However, this relation should be approached with caution The number of subjects was small Statistically significant correlations can certainly address issues of potential theoretical importance such as the role of auditory processes in the development of reading and writing skills. At most, significant negative correlations between performance on the perception tasks and reading and spelling delay provided additional support for a functional relation between discrimination and reading and spelling in developmental dyslexia. For clinical usefulness, however, the reliability of discrimination tests for distinguishing between groups, confidence intervals, and sensitivity and specificity data are needed.

Our data are consistent with the suggestion of Tallal and Stark (1980) that children with secondary linguistic problems are significantly impaired in specific aspects of auditory and phonetic analysis Tallal and Stark (1980) suggested that these lower-level auditory and phonetic disabilities appear to affect directly these children's ability to perform higher-level perceptual, cognitive, and linguistic tasks This view is adhered to by Godfrey et al. (1981). Learning to read and spell presupposes internalized phonemic representations acquired through experience with speech Brady et al (1983) suggested that perceptual difficulties in poor readers are specific to speech We agree with Brady et al (1983) and suggest that if stable speech sound representations have not been developed, problems in reading and spelling may arise

During speech perception the knowledge of linguistic units is not consciously exploited Mattingly (1972) in this context, mentioned that it is reasonable to assume that the process of learning to read serves as the occasion for children to become consciously aware of linguistic units in speech Children with dyslexia may be characterized by having problems in making this additional essential step, i e , to make explicit their linguistic knowledge. Whenever speech perception is affected, this process may be even more aggravated. Speech perception problems may then be viewed as complicating the conditions for adequate reading and spelling processes

### *Speech processing levels.*

At the theoretical level, our results pose some interesting problems It may be useful to characterize speech perception as a series of processes, including a preliminary auditory analysis, further auditory and phonetic feature analysis, and the combination of phonetic features into a phonemic representation (Cutting & Pisoni, 1978, Pisoni & Sawusch, 1975) At any stage in the process of speech perception, information can be placed in short term memory Auditory processing includes a preliminary analysis and is related to auditory short term memory, whereas, phonetic processing includes phonemic labeling strategies and is related to phonetic memory For a detailed discussion on short term memory and its role at different stages of processing, we refer to Baddeley (1992) and Liberman (1996)

There are several stages to phonetic decisions one involving the extraction of auditory properties and one involving the assignment of phonetic features An identification task requires a phonemic judgment, and decisions are based primarily on the phonetic properties and features represented in phonetic short-term memory In a discrimination task, however, not only phonetic information is used but the listener can also base perceptual judgments on auditory speech properties (See Liberman, Harris, Hoffman, & Griffith, 1957, and Studdert-Kennedy, Liberman, Harris, & Cooper, 1970, for the early studies on categorical perception )

We favor an interpretation of identification tasks being relatively more phonetic and discrimination tasks being relatively more auditory in nature Tallal (1974, 1975, 1980) suggests that linguistic impairments are auditory in nature, based on children's inabilities to process rapidly changing spectral information. The implication may be that children with linguistic impairments are unable to clearly apprehend the auditory speech properties that define linguistic categories The results of the present study support Tallal's position

According to a dual-coding structure of auditory and phonetic processing (see e.g., Sawusch & Nusbaum, 1983, Sawusch & Mullenix, 1985), it is not likely for phonetic identification to be normal while auditory discrimination is disturbed. The question is whether or not phonetic identification can develop with problems of auditory processing. From the present study, it seems undeniable that a substantial perceptual component in developmental dyslexia exists with regard to discrimination abilities Groenen, Crul, et al (1996) and Groenen, Maassen, et al. (1996) proposed that the validity of classical models of speech perception should be questioned. A more flexible model than a hierarchical mapping process from the acoustic to phonetic stages seems needed. Because, for both place-of-articulation and voicing, discrimination performance was affected while identification was not, our results support a structure for speech processing with an auditory stage and a phonetic stage partly allowing for stage-independent output. This is a structure in which the integrity of phonetic processing is not totally dependent on the outcome of auditory processing, a view supported by Ades (1977) suggesting the possibility of phonetic processing not receiving input from acoustical traces and instead forming an entirely independent route

An alternative explanation for the fact that discrimination problems can exist without identification problems could lie in subject strategy factors If the dysfunctional discrimination profile of children with developmental dyslexia is a reflection of an abnormal discrimination strategy, then it is not unlikely that the auditory dysfunction may be the result of selective attention Nittrouer and Studdert Kennedy (1987) and Nittrouer (1992) demonstrated that children show different cue weighting strategies than adults Dysfunctional speech perception may be determined by the process of attributing different (yet valid and adequate) weights to acoustic cues in the process of categorization as compared to the cues on which discrimination was based This would allow discrimination performance to be affected while identification was not Such a viewpoint is highly compatible with the fuzzy logical model of speech perception of Massaro (1987, 1992) This viewpoint also seems compatible with the concepts of the WRAPSA model (Word Recognition and Phonetic Structure Acquisition) of Jusczyk (1993). According to Jusczyk, preliminary auditory analysis reflects the inherent organization of the human auditory system The auditory analyzers belong to the innate endowment of the infant. After the development of a weighting scheme, language-specific phonetic decisions can be made. Selective attention within a set of intraphonetic cues, then, seems likely to play a role in phonetic processing It is possible that for children with dyslexia, cues playing a minor role are weighted less in the identification proces. Thus, problems with discrimination of these minor cues may not have as much importance for the identification process as problems in discrimination of more important speech cues. This standpoint seems highly plausible to us because it accounts for the multidimensionality of the speech signal as well as the multidimensionality of the speech processing system Future research with a focus on cue weighting strategies in the perception of multiple-cue speech signals could well provide insight in subject strategy factors applied by dyslexic subjects and, in general by subjects with language problems



### *Sensitive measures*

Brandt and Rosen (1980) studied reading-disabled children who were at least two years behind their age mates in reading level and found no perceptual deficits; whereas, in the present study, perceptual effects were found in children who were at least six months behind their age mates A reason for this apparent discrepancy in results could be that Brandt and Rosen (1980) statistically compared only phoneme boundaries. In the present study, no differences in phoneme boundaries were found either For discrimination, Brandt and Rosen (1980) used correct "same" responses, whereas, we used measures of discriminability ( ln eta) Measures based on signal detection theory are likely to be more sensitive and less prone to contaminating effects of response bias.

Brady et al. (1983) suggested that deficits characteristic of poor readers may stem from material-specific problems of perceptual processing Differences between the results of the Brandt and Rosen (1980) and Godfrey et al. (1981) and our study may be caused by differences in stimulus construction which may in turn have influenced sensitivity. We used resynthesized stimuli; the stimuli were based on a natural voice By manipulating LPC-parameters, specific cues were changed while preserving and controlling for all other aspects This analysis-resynthesis procedure is different from a purely synthesis procedure as is often used in research on speech perception Brandt and Rosen (1980) used a computer controlled parallel resonance synthesizer, Godfrey et al (1981) used a Rockland Model 4516 Digital Speech synthesizer (Rabiner, 1968), Steffens et al (1992), Lieberman et al (1985), and Reed (1989) used the Klatt (1980) cascade-parallel synthesizer. Our choice for using resynthesized instead of synthesized stimuli was based on results of Groenen, Maassen, et al (1996) who directly compared the perception of resynthesized and synthesized speech For the synthesized speech, a text to-speech system that followed the principles of allophonic synthesis was used (Loman, Kerkhoff, &

Boves, 1989) Labeling and discriminability turned out to be poorer for synthetic than for resynthetic stimuli The value for distinguishing a pathological from a control group, however, was not increased by using synthetic speech stimuli, indicating no increase in sensitivity Thus, we conclude that the way in which stimuli are constructed has no major influence on the sensitivity of the perceptual tasks

### *Deviance or delay*

Our results add to those of Godfrey et al (1981) and Reed (1989) Decreased overall levels of discriminability were found for the subjects with dyslexia. Both studies reported less consistent identification near the phoneme boundary However, both studies compared identification results of the experimental group to those of a control group matched on chronological age. The results of Godfrey et al (1981) and Reed (1989), therefore, could be a consequence of reading development In the present study, a similar result was obtained for the identification performance It was shown that for voicing, the children with dyslexia showed a greater degree of ambiguity in identification than the age-matched control group The dyslexic children performed below the level of subjects matched on chronological age This indicates a deficiency in perception ability. However, the dyslexic children performed no worse than subjects matched on reading level which indicates that the level of development in perception is no worse than that of nondyslexic readers This suggests that the deficiency is developmental in nature and implies that neither the dyslexic nor the subjects matched on reading level have the prerequisite skills necessary to learning to read better. Therefore, identification abilities seem to develop along with reading ability. For voicing as well as place of-articulation, the children with dyslexia showed poorer discrimination than both control groups. This suggests discrimination problems to underly developmental dyslexia

The problems associated with dyslexia have proven neither to be of uniform etiology nor to be completely individualized (Ellis, 1984, Lieberman et al., 1985, Watson & Willows, 1995). There have been several attempts to achieve greater specificity in comparisons between dyslexic and non-dyslexic groups The group of subjects with dyslexia in our study was too small to reveal any differences between subgroups (e g , dysphonetic and dyseidetic dyslexics, Boder, 1973) The present study, however, demonstrates that speech perception of children with developmental dyslexia is affected For a better understanding of the etiology of specific developmental language disabilities such as dyslexia, it seems recommendable to consider the child's identification and discrimination abilities. This could result in improved diagnosis of the underlying deficits in developmental dyslexia Hence, the diagnostic identification of those children with dyslexia that show underlying deficits in speech perception may serve as a guide for therapeutic remediation.

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## Footnote

1 Important acoustic cues carrying place-of articulation information are the transitions of the second and third formants and the spectrum of the release burst We decided to manipulate the formant transitions Decisions regarding the voiced voiceless distinction are based on the perceptual integration of several distinct acoustic properties The major acoustic cue carrying voicing information in Dutch is voice onset time (VOT) In addition to the major cue VOT, other minor cues appear to contribute to the voiced voiceless distinction, such as the length of the noise burst, the intensity of the noise burst, the formant transition duration of F1, F2, and F3, and the range of the frequency shift of F1 We chose for manipulating VOT

2 We used a burst appropriate for a /b/ in all the tokens of the place of articulation continuum Dyslexic subjects showed a tendency for lower phoneme boundaries for the place of-articulation continuum than the nondyslexic subjects It has been suggested that children pay more attention to formant transitions and pay less attention to static cues (such as burst spectra) than adults Dyslexic subjects may have affected speech perception abilities and so pay less attention to burst spectra than the control children Ignoring the burst information could explain why they were identifying the stimuli as starting with /d/ earlier than the other subjects

# FORMANT TRANSITION DURATION AND PLACE PERCEPTION IN MISARTICULATING CHILDREN AND ADOLESCENTS

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## Abstract

The explanation of articulatory problems as an output speech disorder does not preclude the possibility that auditory processing problems are associated. Identification of brief auditory spectral cues in a place of-articulation continuum was studied in children with articulation problems Firstly, it was shown that formant transition durations smaller than 20.0 ms dramatically decreased phonemic identification rates for alveolar stop consonants in control subjects. Identification tasks based on two place-of-articulation continua /pɑk/ /tɑk/ with F2/F3 transition durations of 52 and 20 ms were administered to groups of misarticulating children and adolescents and two control groups (children and adults). For all subject groups, there was poorer phonetic processing with shorter transition durations of F2 and F3 The misarticulating subjects demonstrated poorer phonetic processing of formant transitions than the control subjects. Shortening F2/F3 transition duration did not differentially influence perceptually behavior between the experimental and the control groups. In determining the causal link between perception and production, an explanation of perception preceding production was favored. It was argued that in addition to assessing the specificity between perception and production mechanisms, assessment of general perception of formant transitions may have potential as a clinical tool for evaluating phonetic processing.

Functional articulation defects form a large proportion of the disorders in speech pathology (Monnin & Huntington, 1974). The explanation of articulatory problems as an output speech disorder does not preclude the possibility of associated language or language-related problems (Bridgeman & Snowling, 1988, Ekelman & Aram 1983; Groenen, Maassen, Crul, & Thoonen, 1996b; Hall, Jordan, & Robin, 1993; Marion, Sussman, & Marquardt, 1993; Snowling & Stackhouse, 1983)

A developmental relation between speech perception problems and articulatory deficits has been well established. Hoffman, Daniloff, Bengoa, and Schuckers (1985), Hoffman, Stager, and Daniloff (1983) and Ohde and Sharf (1988) found that children with specific articulation problems had problems distinguishing /r/ from /w/. In addition, Monnin and Huntington (1974) found a specific relation between identification and production of /r/-/w/ contrasts in subjects with speech defects. A specific relation between perception and production in children with articulation problems was also found by Broen, Strange, Doyle, and Heller (1983) studying /w/ /r/, /w/-/l/, and /r/-/l/ contrasts, and Raaymakers and Crul (1988) studying the final /s-ts/ contrast. Rvachew and Jamieson (1989) investigated the perception of fricatives in children with a functional articulation disorder. Their results suggested that for a subgroup of children with functional articulation disorders, production errors may reflect speech perception errors

The perceptual significance of formant transitions has been examined in several studies On a psychoacoustical level, Elliot, Hammer, Scholl, Carrell, and Wasowicz (1989a) found discrimination to be significantly better for long transitions compared to short transitions. On a phonological level, formant transition duration was found not only to be an effective cue but but also the primary cue to the stop/glide distinction (Diehl & Walsh, 1989; Walsh & Diehl, 1991). This was confirmed in a study on the influences of formant transition duration on the perception of onset frequency by Porter, Cullen, Collins, and Jackson (1991) They found better use of pitch/timbre cues with longer formant transitions.

The effect of F1 transition duration in speechlike stimuli was studied by Van Wieringen and Pols (1994). They found that when frequency extent is varied, just noticeable differences decreased with increasing transition duration. However, with constant frequency extent, just noticeable differences were found to increase with increasing formant durations

Age-effects in transition perception were demonstrated by Elliot, Hammer, Scholl, & Wasowicz (1989b). Both children and adults required longer transition differences for discrimination than did teenagers and younger adults In addition, longer transitions were more easily discriminated than shorter transitions.

The importance of adequate processing of formant transition duration for adequate speech processing seems indisputable Sussman and Carney (1989) studied labelling of stimuli with variable formant transition duration in adults and children with normal hearing They found differences in the overall shape of the identification functions for the conditions with short and long formant transitions whereas they did not find developmental differences In sum, formant transitions unmistakably play an important role in the processing of speech.

For speech production the intelligibility of speech seems to be partly related to formant transition rate Mulligan et al (1994) found that in amyotrophic lateral sclerosis, intelligibility was strongly related to F2 transition rate Kent et al (1989) found a clear relation between the slope of the F2 transition and speech intelligibility in dysarthric subjects Formant transitions therefore, not only seem to play an important role in the perceptual processing of speech but also in the production and intelligibility of speech

In pathological groups of subjects, the effects of formant transition duration on perception have been studied to a lesser extent Tallal and Piercy (1974, 1975) found that developmental dysphasic subjects demonstrated problems discriminating consonant stimuli with formant transitions of very brief duration The dysphasic children could discriminate only those sounds which did not demand rapid processing and were only able to process transitional acoustic information provided that the transitions were relatively long Riedel and Studdert Kennedy (1985), however, found no differences in performance due to extended transitions and could not systematically distinguish between fluent and nonfluent aphasic subjects Sussman and Carney (1989) mentioned that formant transitions are the important cues on which to concentrate in studying speech perception Formant transition duration, then, may be of value for assessing differences between abnormal and normal auditory processing of speech

Tallal (1990, 1974) indicated that children with specific language impairment have a problem that is based on temporal aspects, resulting in problems with processing rapid cues In the present study, the question was whether children with articulation problems need redundancy in the speech signal as apparent in speech tokens with long F2/F3 transition durations It was questioned whether shortening the duration of the second and third formant transitions would differentially influence the perceptual behavior of groups with articulation problems compared to control groups

Sensitive test for speech pattern audiometry are scarce Hazan et al (1995) recently have proposed a speech perception system in which they make use of specific acoustic speech pattern information They suggest that speech sound continua offer a sensitive tool to assess perception of phonological contrasts Therefore, in the present study, speech sound continua are used A speech continuum consists of a series of speech tokens that vary acoustically for a single phonological contrast The redundancy of the speech signal used presently was reduced by focusing on acoustic cues for a single dimension (i e , the second and third formant transitions for cuing place of articulation) For initial stop consonants, the rapidly changing spectrum provided by the second and third formant transitions forms the most important cue [1]

In Experiment 1, we focused on the effect of reducing the duration of the formant transitions on phonetic perception in adults with normal hearing The results of Experiment 1 provided the stimulus specifications for the speech material used in Experiment 2 In this experiment, the perceptual abilities of children and adolescents with articulation problems and control groups in response to brief auditory spectral cues in a place of articulation continuum were determined All subjects performed identification tasks The hypothesis was that subjects with articulation problems demonstrate more problems in phonetic processing of short formant transitions compared to long formant transitions than subjects without articulation problems

## Experiment 1

### Method

#### *Subjects*

The subjects were eight Dutch adults (five men, three women; mean age 34:2 years, range 19.3 to 56:9 years) with normal hearing All subjects were Dutch native speakers. The majority of Dutch people speak additional foreign languages. Foreign languages are learned from age 12 on, that is, after the critical period of acquiring the native language. Since categorization of subphomenic features is established at very early age (Eimas, 1985), exposure to other languages is not likely to affect perceptual processing of the materials used in this experiment None of the subjects had structural problems in the speech organs or otorhinolaryngologic problems. The subjects did not show hearing loss, as tested by bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985); the maximally allowed hearing loss was 20 dB HL for either ear. The subjects had never been exposed to computer-manipulated speech. For all subjects, Dutch was the native language

#### *Stimuli*

Four speech series, each consisting of five speech tokens with variable formant transition durations of the initial consonant were generated using an LPC-resynthesis procedure[2]. The series differed in place-of-articulation and voicing. We chose for four phonemes: /b/, /d/, /p/, and /t/. All consonants were followed by the same suffix /ɑk/

The starting point for all stimulli was a natural male utterance /bɑk/ (i.e , the Dutch word for *box*) After A/D conversion with a DASH-16 data acquisition board (12 bit sampling at 10 kHz; band-pass filtering between 40 and 5000 Hz, low pass cut off frequency 5000 Hz with a decline of 60 dB/octave), the Interactive Laboratory System (ILS, V6.1, 1989) was used to manipulate the spectral structure of the initial formant transitions. Only the vowel portion (formant transitions plus steady-state vowel) was analyzed with pitch-synchronous linear predictive coding (covariance method: pre-emphasis factor .98, Hamming window), which yielded 12 reflection coefficients (Markel & Gray, 1976) The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients to autoregressive coefficients and then performing a fast Fourier transformation (FFT). The result was smoothed spectrally by interactively adjusting the formant frequencies. F1 started at 400 Hz, linearly increasing in 20 0 ms to a center frequency of 750 Hz. F2 and F3 started at respectively 1000 and 2150 Hz, linearly increasing in 52.0 ms to center frequencies of respectively 1150 and 2500 Hz. The voice lead was cut-back to 71.1 ms. The length of the noise burst was adjusted to 10 ms

Stimulus /dɑk/ (i.e., *roof*) was made accordingly by changing the starting values of the second and third formants to 1500 and 3150 Hz, respectively. To make the voiceless counterparts, voice onset times (VOTs) were increased to 0 ms (see Slis & Cohen, 1969 and Lisker & Abramson, 1964, for the perceptual and acoustical differences between voiceless and voiced consonants in Dutch), yielding /pɑk/ (i.e., *package*) and /tɑk/ (i.e., *twig*). The result was a set of four words (/bɑk/, /dɑk/, /pɑk/, and /tɑk/) with F2 and F3 transition durations of 52 ms.

For each of the four words, the transition durations of the second and third formants were gradually decreased in steps of approximately 10 ms (52.0, 41.3, 30.6, 20.0, and 9.7 ms), preserving the values of the center frequencies and therefore increasing the slopes of the formant transitions. This resulted in four series of five speech tokens (i.e., a total of 20 stimuli).

Sampled data were resynthesized with a pitch-synchronous synthesis procedure by transforming the manipulated reflection coefficients to inverse filter coefficients. Pitch period excitation used a unit pulse. The total length of all voiced stimuli was 381 ms, consisting of (a) voice-lead 71 ms; (b) burst 10 ms, (c) vowel /ɑ/ 150 ms, including the variable duration of F2 and F3 transition; (d) silent interval (occlusion period /k/) 70 ms, and (e) release /k/ 80 ms. The total length of all voiceless stimuli was 310 ms.

In Figure 3.1, schematic formant tracks are presented for the four series of five stimuli.



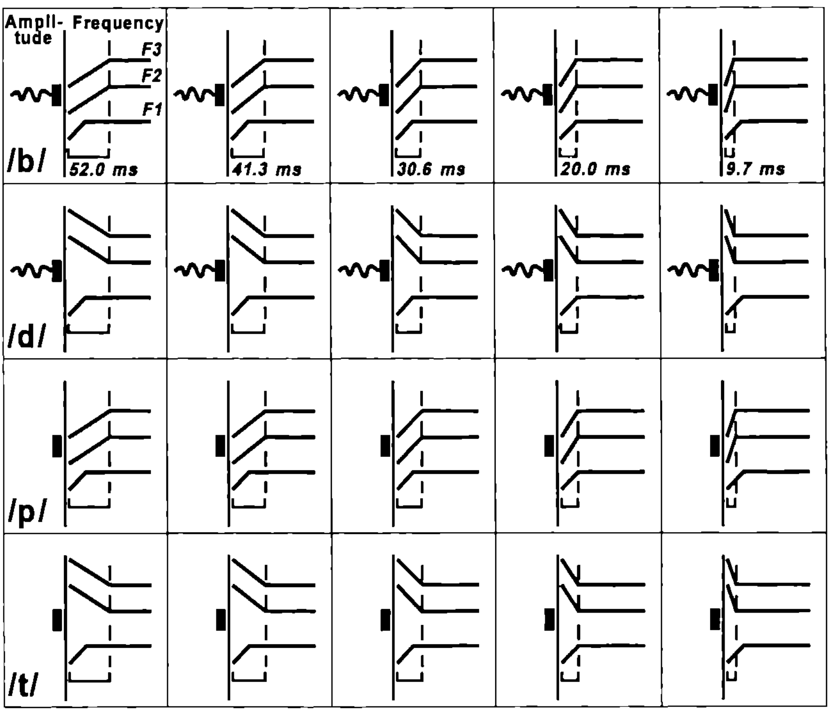


*FIGURE 3.1 Schematic representations of the stimuli for the four series used in Experiment I*

### *Procedure*

The stimuli were recorded and played back using an Ampex 467 DAT tape on a Grundig Fine Arts Digital Audio Tape recorder (type DAT 9000 16 bit D/A converter, 2 fold oversampling, sampling frequency 48 kHz) Presentation was via a Beyerdynamic closed headphone (Type DT770) The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL) Subjects were tested in a quiet room

**TABLE 3 1**
Confusionmatrix for the identification of the speech tokens (percentages)

| | F2/F3 transition duration (ms) | B | D | P | T |
|---|---|---|---|---|---|
| B | 52 0 | 100 | | | - |
| | 41 3 | 100 | | | - |
| | 30 6 | 100 | | | - |
| | 20 0 | 100 | | | - |
| | 9 7 | 97 5 | 2 5 | | - |
| D | 52 0 | | 100 | | - |
| | 41 3 | - | 95 | 2 5 | 2 5 |
| | 30 6 | | 100 | | - |
| | 20 0 | 7 5 | 92 5 | | - |
| | 9 7 | 65 | 35 | | - |
| P | 52 0 | 7 5 | | 92 5 | - |
| | 41 3 | 5 | | 95 | |
| | 30 6 | | | 100 | - |
| | 20 0 | 2 5 | | 95 | 2 5 |
| | 9 7 | 2 5 | | 100 | - |
| T | 52 0 | | 5 | | 95 |
| | 41 3 | | 5 | | 95 |
| | 30 6 | - | | | 100 |
| | 20 0 | - | 2 5 | | 97 5 |
| | 9 7 | - | | 47 5 | 52 5 |

Each subject was examined once in a session of 20 minutes In order to get accustomed to the artificial speech, the subject first listened to four repetitions of each of the four clearest stimuli with F2 and F3 transition durations of 52 ms The identification task was based on a four alternative forced choice procedure and consisted of five repetitions of each of the 20 speech tokens presented in a random order in five series of 20 stimuli The stimuli were separated by an interstimulus interval of 5000 ms The subjects could identify the initial phoneme of the stimulus by marking the appropriate space (/b/, /d/, /p/, or /t/) on a form specially designed for this purpose

## Results

In Table 3.1, the confusionmatrix is given for the identification of the speech tokens. In Figure 3 2, the identification curves are presented for the four phonemes as a function of formant transition duration. On the vertical axis, the percentages correct is displayed.

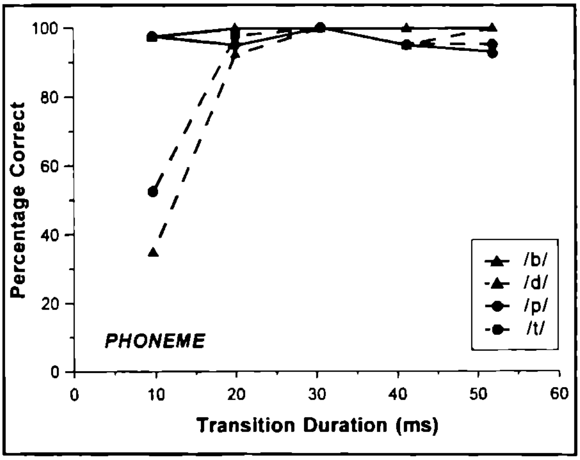


*FIGURE 3 2*
*Identification curves for the four phonemes as a function of formant transition duration On the vertical axis, the 'percentages correct perceived phoneme" are displayed*

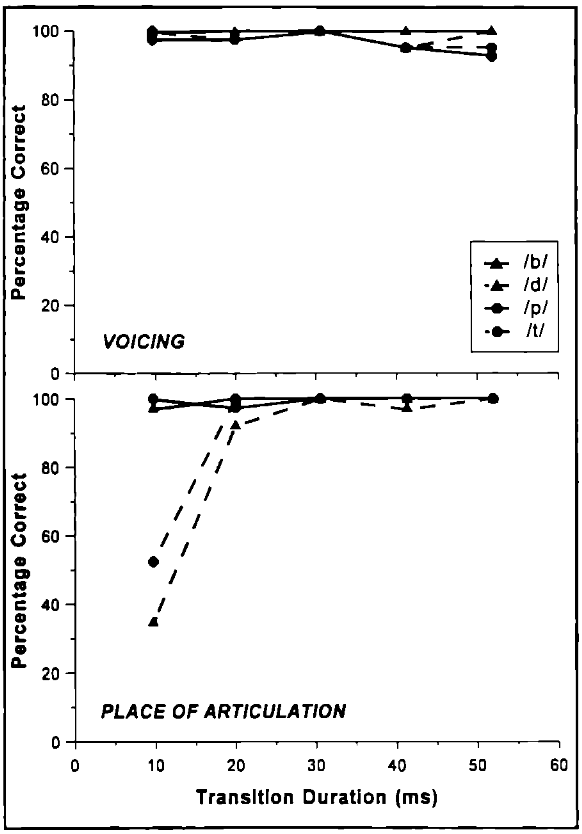


*FIGURE 3 3*
*Identification curves as a function of formant transition duration On the vertical axis, the 'percentages correct perceived voicing" (top) and "percentages correct perceived place of articulation" (bottom) are displayed*

A two factor analysis of variance (Phoneme x Transition Duration) revealed significant effects of Phoneme [$F$ (3,140)=10.03, $p$< 001], Transition Duration [$F$ (3,140)=48 18, $p$< 001], and the interaction Phoneme x Transition Duration [$F$ (12,140)=8.37, $p$<.001]. This indicated that reducing the duration of the formant transitions produced an increasing phonemic error rate The different phonemes did not elicit the same perceptual effect and were not equally influenced by changing formant transition duration. To differentiate the effects, post hoc Student-Newman-Keuls' multiple range tests were performed. The data showed a clear perceptual breakdown when formant transition durations became less than 20.0 ms. As indicated by the significant Phoneme x Transition Duration effect of the ANOVA and confirmed by the post hoc test, this did not apply for all phonemes. Only the alveolar phonemes (/d/ and /t/) were sensitive to changes in formant transition duration.

To check if the greater number of phonemic errors were perceptual place-of-articulation or voicing errors, the data were transformed to "percentage correctly perceived voicing" (Figure 3 3, top) and "percentage correctly perceived place-of-articulation" (Figure 3.3, bottom). A two-factor ANOVA (Phoneme x Transition Duration) on the perceptual place-of-articulation data revealed highly similar effects as the ANOVA on the phoneme data, as did the Student-Newman-Keuls test. The analyses of the perceptual voicing data did not result in significant effects

In sum, formant transition durations smaller than 20 0 ms dramatically decreased phonemic identification rates for initial alveolar stop consonants Perceptual errors solely related to the place-of-articulation feature.

## Experiment 2

In Experiment 1, it was shown that the alveolar stop consonants were sensitive to formant duration changes. Groenen et al (1996b, 1994) showed that children with developmental apraxia of speech and developmental dyslexia showed auditory processing problems for changes in formant transitions in place-of-articulation contrasts Formant transition duration as an independent variable was not addressed in these studies Therefore, in Experiment 2, the clinical value of formant transition duration was investigated. The hypothesis was that subjects with articulation problems demonstrate more problems in phonetic processing of short formant transitions compared to long formant transitions than subjects without articulation problems

Adults with normal hearing and normal articulation demonstrated close to normal processing of initial stop consonants with formant transition durations of 20 ms However, below 20 ms, perception significantly deteriorated. The redundancy of stimuli with formant transitions of 20 ms seemed to be optimally reduced. We chose for using the place-of-articulation continuum /pɑk/-/tɑk/ with (1) formant transition durations of 52 ms, and (2) formant transition durations of 20 ms, respectively All subjects were administered tests of identification.

## Method

### *Subjects*

There were two experimental groups of subjects with articulation problems. The groups differed in age. The group of children with articulation problems consisted of 10 subjects (three girls, seven boys, mean age 9 0 years, range 7·1 to 11:7 years) whereas the group of adolescents consisted of 11 subjects (two girls, nine boys; mean age 14 11 years, range 13·3 to 16:1 years). Both children and adolescents attended special schools for children with language and speech disorders in a Dutch city.

In the pre-selection, information was obtained from medical and educational records; a speech evaluation had also been performed by the school speech-language pathologists. The criteria for inclusion were: (a) identified as misarticulating by school's speech-language pathologist; (b) high rates of multiple speech sound errors; (c) periods of highly unintelligible speech, (d) difficulties with or inability to produce complex phonemic sequences, and (e) receiving therapy for articulation problems and showing slow progress of articulatory speech skills. In addition, information derived from the medical and educational records was used to determine exclusion criteria (see also Groenen et al., 1996b; Thoonen, Maassen, Gabreels, & Schreuder, 1994; Thoonen, Maassen, Wit, Gabreels, & Schreuder, 1995). This information indicated that each selected subject (a) had no structural problems in the speech organs that could be held responsible for their speaking problems; (b) did not have otorhinolaryngologic problems; (c) did not have oral-motor disorders; (d) did not show dysarthric elements in speech; (e) did not have a severe language delay (all subjects were in age-appropriate groups in school, speech-language therapist did not indicate language delays and academic achievement was normal); and (f) did not suffer from severe attention deficits. Each subject with articulation problems functioned within a normal range of intelligence (performance IQ on standardized tests of intelligence was above 85, WISC-R, Wechsler, 1986).

There were two control groups. The first control group consisted of 10 children (mean age 9 1 years, range 7:0 to 11:5 years) attending a regular elementary school. These children were recommended by their teachers. The children did not evidence learning disabilities, a history of hearing problems, speech and language problems, or speech-limiting structural abnormalities Based on school performance and information from the classroom teachers, normal levels of cognitive, motoric, and perceptual functioning could be assumed The control children were gender matched to the children with articulation problems and were in the same school grade, so the educational level was the same across groups The second control group consisted of 10 adults (mean age 36:2 years, range 29·3 to 45.1 years).

All subjects met the following selection criteria. (a) absence of hearing loss on bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985); the maximally allowed hearing loss was 25 dB HL for either ear; (b) no previous exposure to artificial speech; and (c) Dutch as the native language. In addition, only subjects who could correctly identify 11 out of a series of 12 words consisting of six random repetitions of two speech tokens representing the perceptually clearest ends of the speech continua (i.e , /pɑk/ and /tɑk/, F2/F3 transition duration 52 ms) were admitted to the study The probability of obtaining 11 correct responses out of 12 trials based on chance alone was .003. The subjects had to pass this pretest so that we could exclude subjects who had difficulties accommodating to artificial speech. The pretest was administered prior to actual testing, and all of the subjects passed the pretest

### *Stimuli*

The stimuli were constructed, as in Experiment 1, using a single natural male utterance /bɑk/ The consecutive stimuli were generated through manipulation of the linear predictive coding parameters and resynthesis of the result and modifying parts of the oscillographic waveform.

**TABLE 3.2.**
Onset frequencies (in Hz) for the second and third formant transitions

| Stimulus | F2 | F3 | |
|---|---|---|---|
| 1 | 1000 | 2150 | /pɑk/ |
| 2 | 1083 | 2317 | |
| 3 | 1167 | 2483 | |
| 4 | 1250 | 2650 | |
| 5 | 1333 | 2817 | |
| 6 | 1417 | 2983 | |
| 7 | 1500 | 3150 | /tɑk/ |

Two 7-step /p-t/ continua were generated. The consecutive stimuli of each continuum ranged perceptually fom /pɑk/ to /tɑk/ and differed from one another in the starting value of the second and third formant. The onset frequencies of F2 and F3 for each stimulus are shown in Table 3.2 F1 always started at 400 Hz The transition of the first formant was 20 ms in duration. The final 98 ms of the vowel consisted of steady-state formants appropriate for the Dutch vowel /ɑ/ with center frequencies at 750 Hz (F1), 1150 Hz (F2), and 2500 Hz (F3) In one condition, the

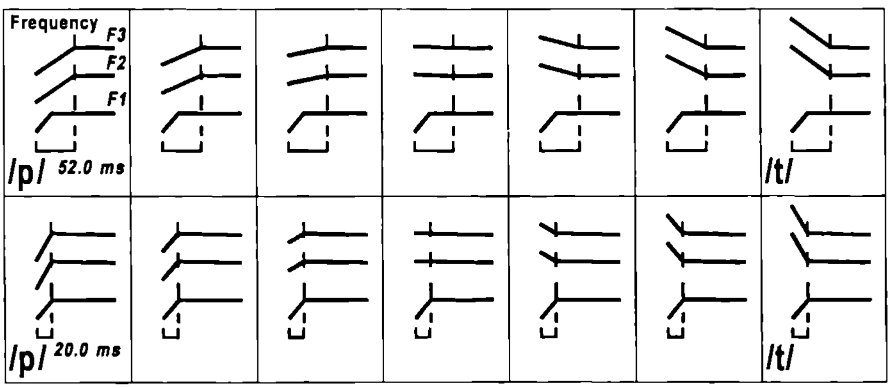


*FIGURE 3 4*
*Schematic representations of the stimuli of the two continua used in Experiment 2*

transition durations of the second and third formants were 52 ms, whereas in the other condition, they were 20 ms.

In Figure 3.4, schematic formant tracks are presented of the stimuli of the two continua.

### *Procedure*

The stimuli were recorded and played back using a portable AIWA Digital Audio Tape recorder (Type AIWA HD-S1: bit-stream D/A converter). Presentation was via a Beyerdynamic closed headphone (Type DT770). The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL). The subjects were tested in a quiet room. The children were tested at the school they were attending.

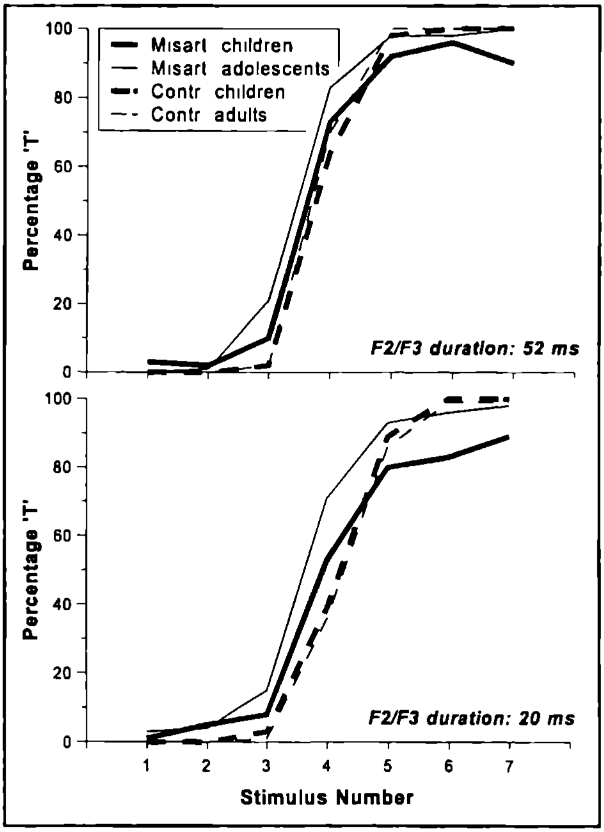


*FIGURE 3 5*
*Mean percentages 'T' responses as a function of stimulus number for the children with articulation problems and the control children and adults for the stimuli with F2/F3 transition durations of 52 ms (top) and 20 ms (bottom)*

Each subject was examined in a session taking approximately 45 minutes. To get accustomed to the artificial speech, the subject first listened to three repetitions of each of the endpoint stimuli from the continua The subject then performed the pretest (identification of 11 out of a series of 12 endpoint stimuli, see subject selection criteria). After this, the subject was administered the identification task.

The identification task was based on a two-alternative forced choice response procedure and consisted of 10 repetitions of each of the 14 speech tokens presented in a random order in five series of 28 stimuli. The stimuli were separated by an interstimulus interval of 3000 ms. The subjects could identify the stimulus by pointing to one of two pictures: a picture of a package, representing the stimulus /pɑk/, or a picture of a twig, representing the stimulus /tɑk/. The subjects were encouraged to respond but never received differential feedback for particular responses

## Results

In Figure 3.5, the mean identification curves for the subjects with articulation problems and the control children and adults for the stimuli with F2/F3 transition durations of 52 ms (top) and 20 ms (bottom) are presented. Each individual identification curve was submitted to probit transformation (Finney, 1971) The probit method determines the value of the phoneme boundary and steepness of the identification function by iteratively computing the cumulative normal distribution that comes closest to the data, using a maximum likelihood criterion. The resulting distribution has a mean (i e., the interpolated 50% crossover point or phoneme boundary) and a standard deviation (i.e., a measure of the variability of scores around the mean). The steepness of the identification function is the reciprocal of the standard deviation and indicates the range of uncertainty in distinguishing one phoneme category from another A high steepness value indicates a small uncertainty range and suggests a highly consistent ability to categorize a speech contrast whereas a low steepness value indicates a large range of uncertainty and suggests difficulties in identifying the speech stimuli.

**TABLE 3.3.**
Mean identification results for the children with articulation problems and the control subjects

| | F2/F3 transition 52 ms | | F2/F3 transition 20 ms | |
|---|---|---|---|---|
| | Phon. boundary | Steepness | Phon. boundary | Steepness |
| **Articulation problems** | | | | |
| Children | 3 78 | 2 10 | 4 38 | 1 42 |
| Adolesc. | 3 46 | 2 16 | 3 69 | 1 69 |
| **Control** | | | | |
| Children | 3 87 | 2 87 | 4 18 | 2.27 |
| Adults | 3 78 | 3 19 | 4 28 | 2 53 |

In Table 3.3, the mean phoneme boundary and steepness of the identification function for the groups are presented. In Figure 3.6, the mean values of the steepness of the identification curves is presented as a function of age A two-factor analysis of variance (unbalanced design) was used to test for differences in the scores The two factors were Group (children with articulation problems, adolescents with articulation problems, control group of children, control group of adults) and Stimulus Type (F2/F3 transitions 52 ms versus 20 ms) with the levels of the latter factor treated as repeated measures

A significant difference in the steepness of the identification function between the 52 ms and 20 ms formant transition duration was found [$F$ (1 37)=16 32, $p$< 001] with a higher score for the condition with transition durations of 52 ms The range of uncertainty was increased by the use of stimuli with shorter transition durations of F2 and F3 There was a significant Group effect for the steepness of the identification function ($F$ (3,37)=5 07 $p$= 005) A Student Newman Keuls test showed that the children and adolescents with articulation problems were not diffe rent from each other The control adults and control children were not different from each other either The adolescents with articulation problems demonstrated lower steepness values than the control adults The children with articulation pro blems showed lower steepness values than the control adults and their age matched control children This indicated that the subjects with articulation pro blems labelled less consistently than the control subjects A significant interaction between Group and Stimulus Type was not found [$F$ (3 37)=0 09 $p$= 96] indicating that the stimuli with short durations of F2/F3 transitions did not improve our abili ty to distinguish subjects with articulation problems from control subjects There were no significant differences in phoneme boundary

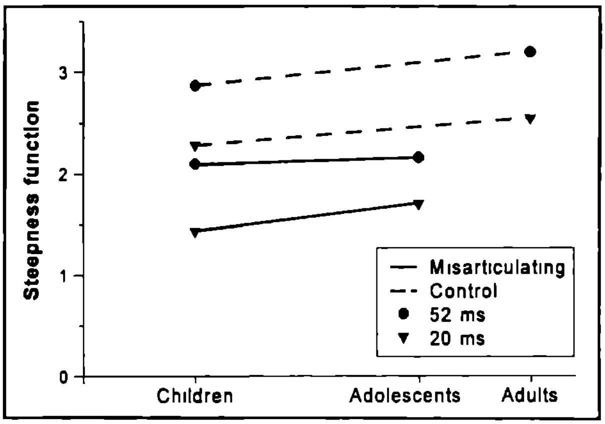


*FIGURE 3 6*
*Mean values of the steep ness of the identification curves as a function of age*



## Discussion

For all subject groups the results with regard to the steepness of the identification function indicated poorer phonetic processing with shorter transition durations of F2 and F3 The children and adolescents with articulation problems showed compa rable phonetic processing of brief formant cues Control adults and control children also demonstrated comparable phonetic processing The adolescents with articula tion problems demonstrated poorer phonetic processing of formant transitions than the control adults The children with articulation problems showed poorer phonetic processing than the control adults and their age matched control children In gene ral, subjects with articulation problems showed affected phonetic processing ability of formant transitions Shortening F2/F3 transition duration did not differentially influence perceptual behavior between the experimental and the control groups

Our results add to results of Hoffman et al (1985) and Monnin and Huntington (1974) Hoffman et al (1985) found phonetic processing problems of the /r/ /w/

distinction in /r/-misarticulating children We found phonetic processing problems of the place-of-articulation contrast /p/-/t/. Monnin and Huntington (1974) found that misarticulating children performed less well on identification than children with normal articulation when stimuli were acoustically degraded. We found the same. Degradation of the speech stimulus by using speech continua resulted in poorer identification, although, further degradation of the speech stimulus by shortening the F2/F3 transition duration did not differentially increase the clinical value Both control groups and experimental groups showed poorer phonetic processing with shorter transition durations of the second and third formant. The ability to categorize was decreased by shortening F2 and F3 transition duration. This result confirms findings by Sussman and Carney (1989) in children and adults without articulation problems and complements findings by Tallal and Piercy (1974, 1975). Tallal and Piercy (1974, 1975) found that language impaired aphasic subjects demonstrated impaired perception of brief acoustic cues, regardless of whether these were steady-state or transitional in character. We found that subjects with articulation problems demonstrated phonetic processing problems of formant transition cues. The difference between the misarticulating subjects and the control groups did not increase when transitions were shortened. The dissimilarity between the results of the present study and those of Tallal and Piercy can be explained by differences in subject groups. Tallal and Piercy studied aphasic subject whereas we studied subjects with articulation problems. Differences can also be explained by methodological factors. Tallal and Piercy focused on discrimination whereas we studied identification. In addition, Tallal and Piercy used brief and long durational cues of 43 ms and 95 ms whereas we used transition durations of 20 ms and 52 ms, respectively.

The children with articulation problems in our study showed high rates of multiple speech sound errors, periods of highly unintelligible speech, difficulties with or inability to produce complex phonemic sequences, and a slow progress of articulatory speech skills The aim of our study was to see whether or not a group of children with articulation problems could be diagnosed as having additional perception problems. We did not correlate the severity of the communication problems to the severity of the problem in perception. Although previous research in children with developmental apraxia of speech by Groenen et al. (1996b) showed that the severity of production problems is closely related to the severity of perception problems, no definite conclusions about this relation can be drawn with regard to the group of children examined in the present study

Speech perception can be characterized by a series of coherent processes, including auditory and phonetic analyses (Cutting & Pisoni, 1978, Pisoni & Sawusch, 1975). Auditory processing includes a preliminary analysis and is related to auditory short-term memory, whereas phonetic processing includes phonemic labelling strategies and is related to phonetic memory (Baddeley, 1992). In the present study, subjects performed identification tasks An identification task requires a phonemic judgment, and thus decisions are based primarily on the phonetic properties and features represented in phonetic short-term memory. (See Liberman, Harris, Hoffman, & Griffith, 1957; and Studdert-Kennedy, Liberman, Harris, & Cooper, 1970, for the early studies on categorical perception.)

The importance of auditory and phonetic processing abilities for the development of language has been studied in children with normally developing language (e g., Nittrouer & Studdert-Kennedy, 1987, Sussman, 1993a) and in children with language impairments (e.g., Groenen , Crul, Maassen, & Van Bon, 1996a, Sussman, 1993b, Tallal & Piercy, 1974, 1975) Groenen et al (1996b) and Groenen, Maassen, Crul, and Hulsmans (1994) showed that children with developmental apraxia of speech and developmental dyslexia showed speech perception problems These problems were found to be related to the discrimination of phonetic cues rather than to the identification of phonetic cues Identification scores are not a direct reflection of the integrity of auditory short term memory but are associated with phonetic memory. Discrimination scores, however, are likely to reflect the integrity of the information in auditory short-term memory A straightforward and seemingly logical conclusion could be that children with developmental apraxia of speech or developmental dyslexia did not have phonetic processing problems An alternative explanation, however, could be that the redundancy of the speech signal was too high and speech cues were perceptually too salient. In the present study, highly sensitized stimulus material was used to assess speech perception processes It was showed that children with articulation problems did show problems in phonetic processing of formant transitions. Locke (1980) emphasized the need for sensitive test procedures to assess central auditory processes. Our findings suggest word initial formant transitions to provide a valuable cue for the construction of speech material to sensitively tap into phonetic processing

It is problematic to establish whether phonetic processing in subjects with articulation disorders was either delayed or deviant Rvachew and Jamieson (1989) suggested that a developmental sequence of the perception of acoustic cues could provide important information about the nature of perceptual deficits associated with disorders in production In the present study, we did not study a developmental sequence. We did, however, examine two groups of articulatory disordered subjects differing in age It was found that phonetic processing of formant transition cues in children with articulation problems did not significantly differ from that in adolescents with articulation disorders. Considering the fact that phonetic processing in children with articulation problems did not significantly differ from that in adolescents with articulation disorders, one may conclude that poorer phonetic processing in subjects with articulation problems reflects a deviance instead of a delay However, since the adolescents with articulation problems did not whereas the children did demonstrate poorer phonetic processing when compared to the control children, one may conclude that poorer phonetic processing reflects a delay instead of a deviance

Simon and Fourcin (1978) studied developmental aspects of categorical perception in normal subjects. Their results suggest that child perception develops gradually from random labelling (at age 2-3), through progressive continuous labelling (at age 3 4) to categorical labelling (from age 5 6 on). These findings were confirmed in a study by Burnham, Earnshaw, and Quinn (1987) They found that between 2 and 6 years a phonological contrast came to be identified increasingly more categorically, whereas, a similar but nonphonological contrast ceased to be identified at all Sussman and Carney (1989) studied developmental aspects of the perception of formant transition cues (with variable durations) and found that subjects after the age of 5-6 years did not show changes in the pattern of labelling stop consonants This is in agreement with our data (from subjects older than 7 years) which showed no significant developmental trend either in the articulatory disordered group or the control group This led us to prefer an explanation of phonetic processing deficits in children with articulation disorders as being deviant instead of delayed in nature There is, however, the possibility that a combination of deviant and delayed perception skills is associated with different types of problems in articulation.

A second unresolved issue is the determination of the causal connection between perception and production There are signs that production can affect perception (e.g , Monnin & Huntington, 1974) Hoffman et al. (1985) hypothesized that productive neutralization may lead to perceptual ignorance Contrary to the idea that production precedes perception, we favor an explanation of perception preceding production. Broen et al. (1983) found that children identified as articulatory delayed showed less discrete categorization of /r/ and /w/ than children with normal articulatory development. Both groups of children, however, misarticulated /r/ as /w/ This finding suggested that normally developing children had developed perceptual ability in advance of production ability. Abberton, Hazan, and Fourcin (1990) also have demonstrated the strong link between perception and production In their study in a group of profoundly deaf children, they suggest that perception precedes production in the sense that categorical labelling is seen for some children who cannot produce the contrast in question Kuhl (1991) has shown that phonetic category prototypes exist at an age of six months, serving as language specific "perceptual magnets" for other stimuli Her results have led to the development of the Native Language Magnet (NLM) theory which describes how innate factors along with experience with a specific language form the development of speech perception (Kuhl, 1993). The WRAPSA model (Jusczyk, 1993) assumes the emphasis on the critical dimensions needed for distinguishing among words in the native language to be developed during the second half of the first year of life. Whereas the WRAPSA (Jusczyk, 1993) and the NLM (Kuhl, 1993) differ in emphasis on lexical/phonological contrast and phonetic categories, respectively, both theories suggest that during the first year of life, prior to the time that infants acquire word meaning and contrastive phonology and prior to the critical time for the development of production skills, essential phonetic perception strategies have been developed

Locke (1980) suggested that standardized tests often assess perceptual ability inappropriately and often concern target phonemes that are not related to the child's articulation errors. Rvachew and Jamieson (1989) add that is it likely that a particular error in production is associated with specific phoneme perception errors, rather than with a general speech deficit Production errors have proven to reflect speech perception errors with regard to specific phonemes and acoustic cues (e g , Broen et al , 1983, Groenen et al., 1996b; Hoffman et al , 1983, 1985; Ohde & Sharf, 1988; Monnin & Huntington, 1974, Raaymakers & Crul, 1988, Rvachew & Jamieson, 1989). This specificity between perception and production is of great value for fundamentally understanding the relation between mechanisms involved in speech perception and speech production In the present study, we have studied the perception of formant transition cues in a group of children with articulation problems which were not constrained to a specific group of phonetic features. In addition to the established specificity between perception and production, we found that misarticulating subjects demonstrated phonetic processing problems of formant transitions. Sussman and Carney (1989) mentioned that formant transitions are the important cues on which to concentrate in studying developmental speech perception Nittrouer (1992) demonstrated that children weight formant transitions more than adults do in making phonetic decisions. We argue that in addition to assessing the specificity between perception and production mechanisms, assessment of general perception of formant transitions in stop consonants may have value as a clinical tool for evaluating phonetic processing Such a tool may consist of a set of perception tasks based on speech tokens with variable consonant structures as to cover all consonantal speech sounds, and variable formant transition durations as to cover degrees of sensitivity in phonetic processing. Hazan et al. (1995) have made great progress in developing such a tool for the english language In our opinion, this approach would offer useful information about central auditory processing with an emphasis on subphonemic psycholinguistic aspects of speech perception It would also provide additional information to the more classical tests on central auditory functioning (e.g., speech in-noise recognition, binaural fusion tasks, filtered speech recognition, time-altered speech recognition) which focus more on psychophysical aspects of speech perception. This, in turn, may help in adjusting and developing rehabilitation programs for misarticulating children.



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## Footnotes

1 Important acoustic cues carrying place information are the transitions of the second and third formants and the spectrum of the release burst. Since synthetic release bursts have not been found to be sufficient cues for place judgments (Syrdal, 1983), we decided to manipulate the formant transitions.

2 Using a LPC-resynthesis procedure for constructing good quality speech tokens can be difficult. We used a method which had been previously applied by Praamstra, Hagoort, Maassen, & Crul (1991). They reported high subjective naturalness ratings of the speech stimuli using the technique.

# PERCEPTION OF VOICING CUES BY CHILDREN WITH EARLY OTITIS MEDIA WITH AND WITHOUT LANGUAGE IMPAIRMENT

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## Abstract

Research on the relationship between early otitis media with effusion (OME), language impairment, and central auditory processing has been equivocal. Identification and discrimination tasks provide us with a sensitive method of assessing speech perception on both an auditory and a phonetic level. The present study examined identification and discrimination of initial bilabial stop consonants differing in voicing by 9-year-old children with a history of severe OME. The groups studied were controlled for language impairment. The ability of these children to perceive major and minor voicing cues was examined using multiple voicing cues. Long-term effects of OME were found for both identification and discrimination performance. Children with OME produced an overall inconsistency in categorization, which suggests poorer phonetic processing. Discrimination was measured by means of "just noticeable differences" (JND). Children with early OME experience demonstrated a greater mean JND than children without early OME experience. Finally, in cases of language impairment with early OME, there was no additional deterioration of auditory or phonetic processing. It appears that either early OME or language impairment can lead to poorer perception.

## Introduction

Otitis media with effusion (OME) is highly prevalent in preschool children (1-4 years) and may cause temporary conductive hearing losses of approximately 20-40 dB (Fria, Cantekin, & Eichler, 1985; Schilder, Zielhuis, & van den Broek, 1993; Silva, Chalmers, & Stewart, 1986). Recurrent periods of partial auditory deprivation in early childhood, the critical time for acquiring speech and language skills, may be associated with placing children at risk for the development of speech, language and hearing skills.

A relationship between early OME and later language problems has been demonstrated in numerous studies (e.g., Holm & Kunze, 1969; Klein, 1988; Sak & Ruben, 1981, see Roberts, Burchinal, Davis, Collier, & Henderson, 1991, for a review) Other studies, however, have found no reliable relationship between early OME and later language problems (see Friel-Patti, 1990; Paradise, 1981; and Roberts et al., 1991, for a review of the relevant publications on receptive and productive language, syntax, and semantics). The occurrence of detrimental long-term effects of OME on language development remains open to question because of conflicting empirical evidence and methodological problems (Downs, 1985; Ventry, 1980). Roberts et al. (1991) stated that the conflicting findings may be caused by two factors: (a) limitations in the methodologies of previous studies (e.g , bad timing of the data collection, incomplete research designs, and poor OME documentation procedures), and (b) interactions between OME and other risk factors Grievink, Peters, van Bon, and Schilder (1993) did a meticulously designed study on the relationship between early OME and later language ability in the same population as the present study In addition to general language ability, they studied higher-order linguistic constructs such as phonologic awareness and word discrimination. Their conclusion was that a history of OME did not have any negative consequences for language performance. A possible interpretation of the conflicting evidence cited thus far is that long-term effects of OME do not show up in language learning processes but are restricted to lower-order speech perception processes.

Welsh, Welsh, and Healy (1985) demonstrated that a significant number of children with early OME had difficulties in central auditory processing using competing sentences, binaural fusion tasks, filtered speech, and compressed speech. They did not find an effect using rapidly alternating speech. Sak and Ruben (1981) found long-term effects of OME only on the auditory reception subtest of the Illinois Test of Psycholinguistic Abilities. Schilder, Snik, Straatman, and van den Broek (1994) examined children from the same birth cohort as the subjects in the present study. They reported a significant effect of OME on speech-in-noise recognition. No effects were reported for filtered speech, binaural fusion, dichotic speech, or auditory memory

Hoffman-Lawless, Keith, and Cotton (1981) and Locke (1980a, 1980b) stated that the major methodological shortcomings of auditory studies had to do with the use of insensitive test procedures and confounding of OME with language impairment Eimas and Clarkson (1986) and Clarkson, Eimas, and Cameron-Marean (1989) used speech continua in combination with identification and discrimination tasks in the assessment of speech processing in children with a history of OME. These tasks have proven to be quite sensitive in assessing central auditory functioning (Repp, 1984). Clarkson et al. (1989) studied the perception of voicing in children age 5 5 years. Their identification and discrimination tasks were based on stimuli varying in one cue· voice onset time (VOT). They found that children with early OME showed poorer discrimination performance. However, only children with language impairments and early OME showed poorer categorization To further disentangle the effect of OME and language delay a full factorial subject design would be required. However, Clarkson et al. (1989) studied only three groups of subjects. (a) children with OME and language delay, (b) children with OME only, and (c) children without OME or language delay.

To allow for subtle perceptual effects to appear, in the present study we used identification and discrimination tasks with speech continua that varied by small acoustic steps. In an identification task requiring a phonemic judgment, decisions are based on the phonetic properties. In a discrimination task, decisions may be based on both phonetic and auditory properties (Pisoni, 1973; Pisoni & Tash, 1975). To take into account the potentially confounding effect of language impairment, we employed a factorial design consisting of two factors: (a) history of recurrent OME, and (b) language impairment.

Decisions regarding the voiced-voiceless distinction are based on the perceptual integration of several distinct acoustic properties The major acoustic cue carrying voicing information in Dutch is voice onset time (VOT) (Lisker & Abramson, 1964; Slis & Cohen, 1969a). In addition to the major cue VOT, other minor cues appear to contribute to the voiced-voiceless distinction (Lisker, 1975; Massaro, 1975; Schouten & Pols, 1983, Slis & Cohen, 1969a, 1969b). Multiple cues can combine to signal a phonetic distinction and thereby enhance phonetic clarity and discriminability. Conflicting multiple cues decrease clarity and discriminability (Best, Morrongiello, & Robson, 1981; Fitch, Halwes, Erickson, & Liberman, 1980; Repp, 1981a). Because categorization strategies contribute to discrimination performance, the sensitivity of the discrimination task can be increased by using a cooperating as well as a conflicting-cues continuum. In the latter condition the effect of categorization on perceptual discrimination is reduced as compared to the cooperating-cues condition, whereas acoustic distances between stimuli are equal.

The topic of auditory versus phonetic processing of speech has been neglected in research on the long-term effects of OME. The importance of auditory and/or phonetic processing abilities for the development of language has been studied in children with normally developing language (e.g., Nittrouer & Studdert-Kennedy, 1987, Sussman, 1993a; Sussman & Carney, 1989) and in children with language impairments (e.g., Elliott & Hammer, 1988; Sussman, 1993b, Tallal & Piercy, 1974, 1975)

The use of two continua with (a) cooperating cues and (b) conflicting cues not only increases sensitivity, but also contributes to the differentiation of auditory from phonetic processing in the discrimination task. Both continua vary from [bαk] to [pαk] according to differences in VOT. In the case of cooperating cues, the major and minor cues both lead to the same percept and thereby enhance perceptual clarity. In the case of conflicting cues, the major and minor cues lead to percepts in opposite phonemic directions and normally elicit phonetic neutralization. Using both conflicting and cooperating cue conditions enables us to differentiate auditory from phonetic processing. In the discrimination tasks, the absolute acoustic inter-stimulus differences of each pair of the cooperating-cues continuum are equal to the counterpart pair of the conflicting-cues continuum. If discrimination is based solely on auditory information, then there should be total similarity between the discrimination curves in the cooperating cues and the conflicting-cues condition. However, if discrimination is (partly) based on phonetic processing strategies, a difference between conditions should occur.

To summarize, our study extends previous research in several ways by (a) implementing a prospective cohort design, using a reliable OME documentation procedure (tympanometric screening of OME every three months between the ages of two and four years) and controlling for risk factors (e.g , intelligence, grade level in school, ventilating tubes), (b) maintaining a complete four-cell factorial design (early OME and language impairment), (c) using sensitive measurement materials and procedures (speech continua, and cooperating and conflicting cues conditions), (d) separating auditory from phonetic processing (by using identification and discrimination tasks with both cooperating and conflicting cues), and (e) studying voicing as a multidimensional feature determined by a major cue (VOT) and a number of minor cues

We expected that, because of recurrent periods of partial auditory deprivation in early childhood, long-term effects of OME would exist, either in auditory or phonetic processing In addition, we expected that language impairment also would result in poorer processing of speech.

Experiment 1 focuses on stimulus construction The conflicting power of combined minor voicing cues was determined In Experiment 2 the speech perception abilities in children with OME, with and without language impairment, are assessed

## Experiment 1

Before generating the speech continua a study was conducted to determine the conflicting power of minor voicing cues. In comparison with the English voicing distinction, the Dutch voicing distinction is differently distributed along the VOT dimension Whereas the English values fall into a range between 0 and +100 ms, Dutch stop-category values fall into a range between -100 and +10 ms (Lisker & Abramson, 1964).

We made use of four minor cues: (a) the length of the noise burst; (b) the intensity of the noise burst; (c) the formant transition duration of F1, F2, and F3, and (d) the range of the frequency shift of F1

### Method

#### *Subjects*

Subjects were 10 Dutch adults with normal hearing (5 men, 5 women; mean age 36:4 (years:months) with a range of 25:4-56:4). All of the subjects met the following selection criteria: (a) normal bilateral pure-tone audiometric thresholds (no greater than 20dB HL) at 250, 500, 1000, 2000 and 4000 Hz (ISO, 1985) immediately before to testing, (b) Dutch as the native language, and (c) no enrollment in otological medical/surgical treatment.

### *Stimuli*

The starting point for the stimuli was a naturally produced syllable, [bɑk], spoken by an adult male. This utterance was band-pass filtered between 40 and 5000 Hz (60 dB/octave attenuation), then digitized at a rate of 10 kHz with a DASH-16 data-acquisition card (12 bits resolution). The Interactive Laboratory System (ILS, V6.1, 1989) was used to smooth the spectral structure For smoothing, the vowel (formant transitions plus steady state vowel) was analyzed with pitch synchronous linear predictive coding (covariance method: pre emphasis factor .98, Hamming window), yielding 12 reflection coefficients (Markel & Gray, 1976). The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients into autoregressive coefficients and then performing a fast Fourier transformation (FFT)

The formant frequencies were interactively adjusted. The first formant (F1) started at 400 Hz and linearly increased to a center frequency of 750 Hz by 20 ms. The second (F2) and third (F3) formants started at 1000 and 2150 Hz, respectively, and linearly increased to center frequencies of 1150 and 2500 Hz, respectively, by 52 ms. The sampled data were resynthesized with a pitch synchronous synthesis procedure by transforming the changed reflection coefficients to inverse filter coefficients. The filter was excitated using a pulse train. The resynthesized vowel part was spliced onto the initial stop consonant The temporal structure was adjusted by setting the length of the burst to 10 ms. The intensity of the burst was -11.4 dB (relative to the sound level of the vowel)

**TABLE 4.1.**
Stimulus specifications for conflicting minor cues.

| | Burst intensity (dB relative to vowel) | Burst length (ms) | Transition duration (ms) F1/(F2 and F3) | Frequency shift F1 (Hz) |
|---|---|---|---|---|
| **Voiced (VOT=-19.1 ms)** | | | | |
| 0 (original) | -11 4 | 10 | 20/52 | 350 (400-750) |
| 1 | -7.3 | 14 | 20/20 | 0 (750-750) |
| 2 | -3 1 | 22 | 20/20 | 0 (750-750) |
| 3 | 1.1 | 30 | 20/20 | 0 (750-750) |
| **Voiceless (VOT=0 ms)** | | | | |
| 0 (original) | -11.4 | 10 | 20/52 | 350 (400-750) |
| 1 | -14.6 | 8 | 52/52 | 550 (200-750) |
| 2 | -17.7 | 4 | 52/52 | 550 (200-750) |
| 3 | -20 8 | 0 | 52/52 | 550 (200-750) |

If stimuli unambiguously belong to the same phonetic category, phonetic neutralization in discrimination tasks disappears (Repp, 1981b). This suggests that perceptual neutralization occurs near phoneme boundary regions. In the first step, two syllables with VOT values near the phoneme boundary were selected in the following way. We constructed 11 stimuli differing in about 10-ms VOT steps between -71.1 and +24 ms from /bɑk/ (i.e., *box*) to /pɑk/ (i.e., *package*) The phonemic quality of the tokens was checked in a pilot study by having 10 adults with normal hearing label 10 repetitions of each of the 11 stimuli presented in random order. The mean phonemic boundary occurred at a VOT of -11.31 ms (a value in conformity with the Dutch language). The nearest unambiguously labeled voiced stimulus /bɑk/ had a VOT of -19 1 ms (mean percentage /b/ of 90%) The nearest unambiguously labeled voiceless stimulus /pɑk/ had a VOT of 0 ms (mean percentage /p/ of 99.33%). These two speech tokens were then used as reference stimuli when determining the conflicting potential of the minor cues.

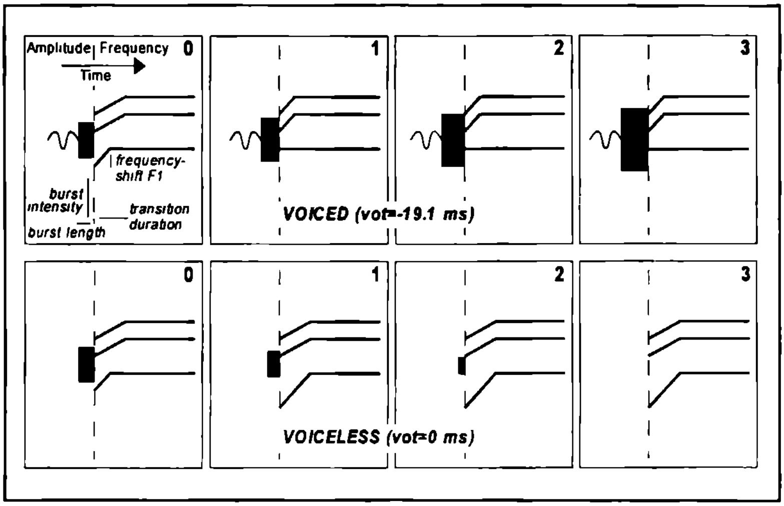



*FIGURE 4 1 Abstract representation of the stimuli in Experiment 1 The wave form at the start of each of the upper graphs represents the amount of glottal pulsing before the opening of the mouth (VOT = 19 1ms) The filled in rectangles designate burst properties (width = burst length, and height = burst intensity) The numbers in the upper right corner of each graph correspond to the levels of conflicting voicing information*

We incorporated four minor voicing cues into our stimuli· (a) the intensity of the noise burst (low=voiced, high=voiceless); (b) the length of the noise burst (short =voiced, long=voiceless); (c) the formant transition duration of F1, F2, and F3, (long= voiced, short=voiceless); and (d) the range of the frequency shift of F1 (large=voiced, small=voiceless). Four levels were created involving all four minor cues for each of the reference stimuli. This resulted in a total of eight stimuli (see Table 4.1 for the exact stimulus specifications and Figure 4.1 for an abstract representation of the stimuli)

### *Procedure*

Stimuli were recorded and played back using an Ampex 467 DAT-tape on a Grundig Fine Arts Digital Audio Tape recorder (type DAT-9000. 16 bit D/A converter, 2-fold oversampling, sampling frequency 48 kHz). Presentation was via a Beyerdynamic closed headphone (Type DT770). Playback level was set at a listening level of 70dB HL, a level judged by all subjects to be comfortable. Subjects were tested in a quiet room

Each of the 10 subjects was examined for one session of 30 minutes The identification task was based on a two-alternative forced choice procedure (one stimulus was presented and subjects responded with one of two response alternatives) and consisted of five repetitions of each of the eight stimuli presented in random order as five series of eight stimuli. The stimuli were separated by an interstimulus interval of 2500 ms. Subjects identified the initial speech sound of the stimulus by writing it down on a form designed for this purpose. All subjects were required to pass the criterion of correctly identifying four out of five presentations of each of the two original stimuli /bɑk/ and /pɑk/. Out of a total of 10 subjects, 9 met the criterion. The perceptual data from these 9 subjects (5 men, 4 women) were then analyzed.

## Results

The effect of the minor cues is presented in Figure 4.2 The solid lines indicate the effect of the minor cues on the perception of /b/ (VOT=-19.1 ms). The dashed lines indicate the effect of the minor cues on the perception of /p/ (VOT=0 ms). The percentage /b/-judgments for the two reference stimuli changed as a function of the minor cues. The slope (*b*) of the phonemic shift (estimated with linear regression analysis) corresponds to the power of the combined minor cues to elicit phonetic neutralization Slope values were significantly different from zero for both /bɑk/ and /pɑk/ ($b$=-9.33, $t$ [34]=-2.414, $p$=.021 and $b$=-10.89, $t$ [34]=-4.051, $p$<.001, respectively).

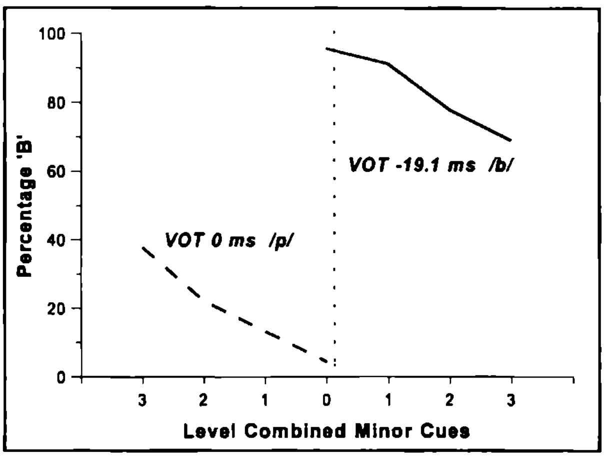



*FIGURE 4 2*
*Mean identification scores as a function of combined conflicting dimensions*

In this experiment the conflicting power of the minor voicing cues was established. The results validated the choice of the amount of conflicting and cooperating voicing information used to generate the voicing continua for Experiment 2.

## Experiment 2

In this experiment speech perception of voicing in children with OME with and without language impairment was assessed.

### Method

#### *Subjects*



The factorial design consisted of four cells formed by the presence and absence of language disabilities and by the presence and absence of a history of OME: (a) OME/Language Impairment; (b) OME only; (c) Language Impairment only; and (d) neither OME nor Language Impairment, i.e , the control group (C).

Subjects were selected from the Nijmegen Otitis Media Group, a birth cohort of over 1,400 children born in Nijmegen (The Netherlands) between September 1, 1982, and August 31, 1983. These children were involved in an earlier study of the efficacy of screening preschoolers for OME (Zielhuis, Rach, & van den Broek, 1989) Over 1,300 children were screened for OME using tympanometry every three months between the ages of two and four years, which led to nine sessions per child. The tympanometric results were classified into four types according to a modified version of the method described by Jerger (1970)· (a) type A. maximum compliance > 0.2 ml at an ear canal pressure of -99 dPa or higher, (b) type C1· maximum compliance > 0 2 ml at an ear canal pressure between -100 dPa and -199 dPa, (c) type C2 maximum compliance > 0 2 ml at an ear canal pressure between -200 dPa and -399 dPa, (d) type B: maximum compliance < 0.2 ml at an ear canal pressure below -400 dPa. Only a type B tympanogram (i e., little or no change in compliance of the middle ear) was taken as evidence of OME. At about eight years of age, over 300 of the children participated in a follow-up study (see Grievink et al., 1993) This study included several language development tests and questionnaires from the teachers and parents, respectively. The subjects in the present study were selected from this group of children

The presence/absence of a history of OME was determined by the frequency of type B tympanograms for both ears simultaneously (presence: at least four times, absence zero times). The presence/absence of language impairment was determined by four variables. Two subtests of the "Language Tests for Children" ("Taaltests voor Kinderen," van Bon, 1984) were used (a) the "Word Forms Production" test ("Woordvormen Produktie" test), which is a productive morphological test concerned with knowledge of word forms, and (b) the "Concealed Meaning" test ("Verzwegen Betekenis" test), which is a receptive test concerned with the child's understanding of the nonexplicit contents of sentences. Both tests have been shown to be related to different specific language factors (van Bon, 1984). The other two variables used to determine the presence/absence of a language impairment were the data from questionnaires administered to (c) the parents and (d) the teachers. Factor analyses on each questionnaire yielded factor scores of a set of preselected items loading high on general linguistic competence (see the Appendix for details of the analyses used).

**TABLE 4.2**
Means for variables used to select three experimental groups and one control group

| | OME/LI | OME | LI | Control |
|---|---|---|---|---|
| N | 10 | 12 | 10 | 12 |
| boys/girls | 6/4 | 2/10 | 3/7 | 5/7 |
| Age | 8,11 | 9,0 | 9,2 | 8,11 |
| **OME** | | | | |
| Freq type B | 4 9 | 5 3 | 0 0 | 0 0 |
| **Language Impairment** | | | | |
| "Word F. Prod." | 4.0 | 6 6 | 3 6 | 7 3 |
| "Conc. Mean " | 3 3 | 7.5 | 3 5 | 6 7 |
| Quest teachers | -0 2 | 0 6 | 0 2 | 0 6 |
| Quest parents | -0 7 | 0 5 | -0 4 | 0 4 |

**Note.**
OME = history of Otitis Media with Effusion; LI = Language Impairment. The scores on the "Word Forms Production" test and the "Concealed Meaning" test are standard scores, a score above 5 0 indicates higher than normal linguistic competence and a score below 5 0 indicates lower than normal linguistic competence. The scores on the questionnaires are factor scores based on a set of selected items

In Table 4.2, the means for the variables used to select the subjects are presented. The means for the OME/Language Impairment group and the Language Impairment group on the "Word Forms Production" test, the "Concealed Meaning" test, the teacher questionnaires, and the parent questionnaire were all more than three standard deviations from the means for the control group. The means for the OME group were all within a single standard deviation from the mean for the control group.

A two-factor analysis of variance (OME [absence/presence] x Language Impairment [absence/presence]) was used to verify the significance of differences in the selection scores. This resulted in a significant effect of OME for frequency of type B tympanogram ($F$ [1,40]=321.2, $p$<.001) and significant effects of Language Impairment for the "Word Forms Production" test, the "Concealed Meaning" test, and the questionnaires filled out by the teachers and parents ($F$ [1,40]=106 0, $p$<.001; $F$ [1,40]=107.29, $p$<.001; $F$ [1,40]=14.13, $p$< 001 and $F$ [1,40]=22.36, $p$< 001, respectively). There was no significant interaction between OME and Language Impairment for either frequency of Type B tympanogram ($F$ [1,40]=0.58, $p$=.45), "Word Forms Production" test ($F$ [1,40]=3.49, $p$=.07), the "Concealed Meaning" test ($F$ [1,40]=1.84, $p$=.18), and the questionnaires filled out by the teachers and parents ($F$ [1,40]=0.0, $p$= 98 and $F$ [1,40]=0 63, $p$=.43, respectively) These control statistics confirmed that the cells of the factorial design were appropriately filled.

Further, all of the children met the following selection criteria: (a) normal bilateral pure tone audiometric thresholds (no greater than 20 dB HL) at 250, 500, 1000, 2000 and 4000 Hz (ISO, 1985) immediately before testing, (b) normal speech-in-noise recognition (S/N ratio 0 dB, presented at 70 dB HL), measured on two series of 10 monosyllabic words immediately after testing (scored was the percentage of correctly perceived phonemes; a score within 1 standard deviation from the mean of the control group was considered normal; none of the experimental groups differed significantly from the control group), (c) sufficient intellectual capacities (as measured by the Coloured Progressive Matrices for children, Raven, 1965); a standard score of at least 50 was considered sufficient, (d) no bilingualism, (e) Dutch as the native language; (f) no ventilating tubes inserted in the tympanic membrane at the time of testing nor during earlier phases of OME; (g) no enrollment in medical/surgical treatment; (h) no severe speech production problems; and (i) no missing values on any of the selection variables. All subjects attended regular schools and were in grade levels appropriate for their age.

### *Stimuli: Generating the Two Continua*

Two eight step /b-p/ continua were generated. By manipulation of the linear predictive coding parameters and resynthesis in combination with modifying parts of the oscillographic waveform, the consecutive stimuli of both continua were constructed

TABLE 4.3.
Stimulus specifications for the cooperating-cues and conflicting cues continua

| | VOT (ms) | Burst intensity (dB rel. to vowel) | Burst length (ms) | Transition duration (ms) (F1/F2 & F3) | Frequency shift F1 (Hz) |
|---|---|---|---|---|---|
| **Cooperating cues** | | | | | |
| 1 | 52.7 | -17.7 | 4 | 52/52 | 550 |
| 2 | -40.9 | -17.7 | 4 | 52/52 | 550 |
| 3 | -29.1 | -17.7 | 4 | 52/52 | 550 |
| 4 | -19.1 | 17.7 | 4 | 52/52 | 550 |
| 5 | -10.8 | -10.4 | 13 | 31/31* | 275 |
| 6 | 0.0 | -3.1 | 22 | 20/20 | 0 |
| 7 | 8.0 | -3.1 | 22 | 20/20 | 0 |
| 8 | 16.0 | -3.1 | 22 | 20/20 | 0 |
| **Conflicting cues** | | | | | |
| 1 | -52.7 | -3.1 | 22 | 20/20 | 0 |
| 2 | -40.9 | -3.1 | 22 | 20/20 | 0 |
| 3 | -29.1 | -3.1 | 22 | 20/20 | 0 |
| 4 | -19.1 | -3.1 | 22 | 20/20 | 0 |
| 5 | -10.8 | 10.4 | 13 | 31/31 | 275 |
| 6 | 0.0 | -17.7 | 4 | 52/52 | 550 |
| 7 | 8.0 | -17.7 | 4 | 52/52 | 550 |
| 8 | 16.0 | 17.7 | 4 | 52/52 | 550 |

Note.
VOT = Voice Onset Time.
* Due to the use of a pitch synchronous LPC procedure, the appropriate value of 36 ms was not possible. Instead we chose a value of 31 ms.

The cooperating-cues continuum consisted of stimuli with major and minor voicing cues that represented the same voicing state. This continuum started with /b/ and moved in the direction of /p/. The conflicting-cues continuum consisted of stimuli with major and minor cues working in opposite phonemic directions.

In order to construct appropriate cooperating-cues and conflicting-cues voicing continua, stimulus specifications have to be chosen carefully Two major considerations constrain the choice of the stimulus specifications (1) the specifications must be within the limits defined by the acoustic effects of natural articulation, i e. the parameters chosen to synthesize speech must reflect normal human articulation, and (2) the specifications should permit perceptual neutralization to take place.

We chose reference stimuli with conflicting minor cues specifications that elicited 20-25% /p/ responses for the /bɑk/ reference stimulus and 20-25% /b/-responses for the /pɑk/ reference stimulus In Figure 4.2, the levels indicated by '2' were judged to offer the appropiate stimulus conditions. These levels were fixed at VOT-values outside the values of the reference stimuli and linearly interpolated at VOT-values between the values of the reference stimuli. Hence, the minor cues were varied in a block. Table 4.3 lists the stimulus specifications for both the cooperating-cues and the conflicting-cues continua.

### *Procedure*

The stimuli were recorded as in Experiment 1 and played back using a portable AIWA Digital Audio Tape Recorder (Type AIWA HD-S1. bit-stream D/A converter) They were presented via the same headphones as in Experiment 1. The playback level was set at the level judged as comfortable by the subject (always close to 70 dB HL). The subjects were tested in a quiet room at the school they were attending.

Each child was examined in a one-hour session. In order to accustom the child to the manipulated speech, he or she first heard four repetitions of the endpoint stimuli from the two different continua without having to respond This was followed by a training trial of a series of 12 repetitions of the endpoint tokens of the cooperating-cues continuum. The subject had to meet the criterion of identifying 10 out of 12 correctly All subjects met this criterion.

The identification task consisted of a two-alternative forced choice response to a single auditory stimulus Eight repetitions of each of the 16 stimuli (total of the two continua) were presented in a random order consisting of eight blocks of 16 stimuli each. The stimuli were separated by an interstimulus interval of 3500 ms. Subjects could identify the stimulus by pointing to one of two pictures, a picture of a box, representing the stimulus /bɑk/, and a picture of a package, representing the stimulus /pɑk/.

The AX discrimination task required a response of "same" or "different" on each trial. In order to obtain a bias-free measure of discriminability, the tasks were set up in such a way that signal detection measures could be applied (Coombs, Dawes & Tversky, 1970). For this, each task contained physically different as well as identical pairs. There were two separate discrimination tasks, one for the cooperating-cues and one for the conflicting-cues continuum In both tasks the subjects heard two series of 27 discrimination pairs. Each series contained two repetitions of the physically identical pairs 2-2, 3-3, 4-4, 5-5, 6-6, 7-7, and three repetitions of the physically different pairs consisting of stimulus 2 (/bɑk/), the so-called anchor stimulus for which the JND was being measured; this resulted in pairs 2-3, 2-4, 2-5, 2-6 and 2-7. The "anchor" stimulus was always in first position in the pair. All pairs in one series were randomly ordered with an intrapair interval of 400 ms and an interpair interval of 3500 ms.

The subjects were asked to point to a picture containing a triangle and a circle when the words in the pair they heard sounded different and simply not to respond when the words in the pair they heard sounded the same. Half of the subjects started with the stimuli from the cooperating-cues continuum, and half of the subjects started with the stimuli from the conflicting-cues continuum. The children were motivated to respond by randomly verbally reinforcing responses throughout the experiment. In addition the subjects knew they were to receive a small present for cooperation after finishing the tasks. Subjects never received differential feedback for particular responses.

All subjects first performed the identification task with four series of 16 stimuli and then one of the discrimination tasks. After a short break, the subjects performed the identification task with the remaining four series of 16 stimuli and the other discrimination task.

*FIGURE 4 3*
*Mean percentage of 'P' responses as a function of stimulus number on the cooperating cues continuum*

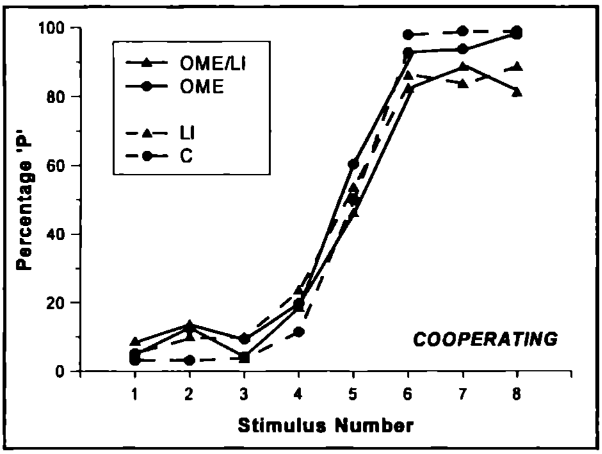
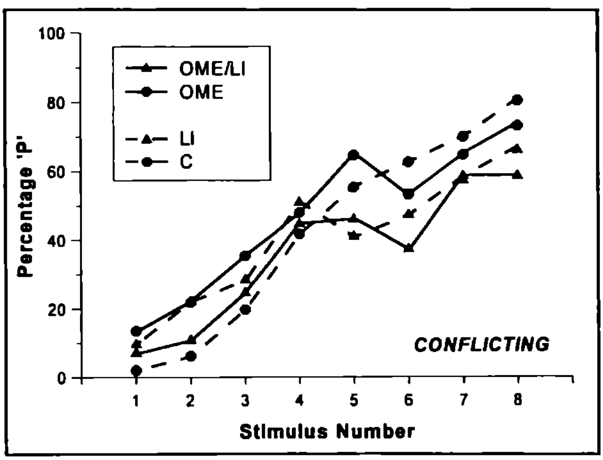



*FIGURE 4 4*
*Mean percentage of 'P' responses as a function of stimulus number on the conflicting cues continuum*



### Identification

Figures 4 3 and 4 4 display the mean identification curves for the four groups in the cooperating-cues and the conflicting-cues conditions, respectively Each individual identification curve was submitted to probit transformations (Finney, 1971) yielding slope values and phoneme boundary values. A high slope value indicates a small uncertainty range and suggests a highly consistent ability to categorize a speech contrast, whereas a low slope value indicates a large range and suggests difficulty in the identification of a speech contrast. Table 4.4 shows the mean phoneme boundary and slope scores for the four groups. Figure 4.5 displays the individual slope scores for the subjects in the cooperating-cues and the conflicting-cues conditions.

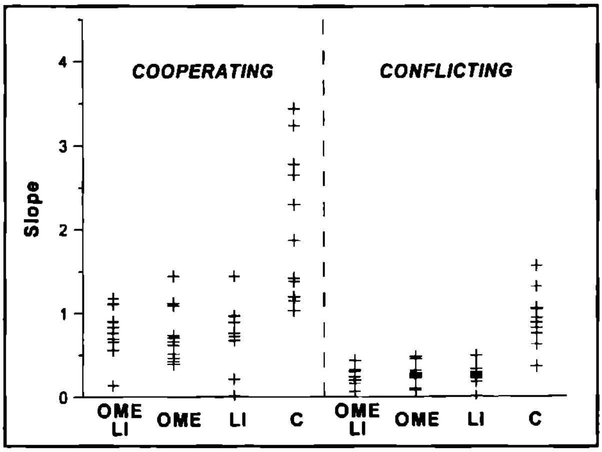
**TABLE 4.4.**
Mean identification results for the four groups.

| | Phoneme boundary | | Slope | |
|---|---|---|---|---|
| | M | SD | M | SD |
| **Cooperating cues** | | | | |
| OME/LI | 5 51 | 0.64 | 0 80 | 0.30 |
| OME | 4.59 | 0.42 | 0.80 | 0.36 |
| LI | 6 08 | 0 60 | 0.81 | 0 43 |
| Control | 4.80 | 0.45 | 1.96 | 0.84 |
| **Conflicting cues** | | | | |
| OME/LI | 7.72 | 1.45 | 0.24 | 0.10 |
| OME | 5.31 | 1 97 | 0 29 | 0.12 |
| LI | 6 57 | 1 88 | 0 23 | 0 14 |
| Control | 5 41 | 1.20 | 0 75 | 0 30 |

**Note.**
OME = history of Otitis Media with Effusion, LI = Language Impairment

For both the phoneme boundary scores and the slope scores a three-factor analysis of variance was used to test for significant differences. The three factors were OME (levels: presence versus absence), Language Impairment (levels: presence versus absence) and Stimulus Type (levels. cooperating versus conflicting cues) with the levels of Stimulus Type treated as repeated measures. Hence, in the factor OME, the subject groups OME/LI and OME represented the presence of early OME, whereas the subject groups LI and Control represented the absence of early OME. In the factor Language Impairment, the subject groups OME/ LI and LI represented the presence of language impairment, whereas the subject groups OME and Control represented the absence of language impairment.

FIGURE 4 5
*Individual slope scores for all four groups on the cooperating cues and the conflicting cues continuum*




There was a significant mean slope difference between stimulus types (Stimulus Type: $F[1,40]=21.9$, $p<.001$), which indicates that stimuli in the cooperating-cues continuum were less ambiguously perceived when compared to the stimuli in the conflicting-cues continuum. In addition, there were significant slope effects of OME, Language Impairment, and the interaction term OME x Language Impairment ($F[1,40]=6.20$, $p=.017$; $F[1,40]=6.77$, $p=.013$; $F[1,40]=6.06$, $p=.018$, respectively). A posthoc Tukey (HSD) studentized range test ($p=.05$) showed that the control group had significantly higher slope scores than either experimental group in both the cooperating cues and the conflicting-cues conditions The three experimental groups were not significantly different from each other. The results and the data of Table 4.4 indicate that children with either early OME experience or language impairment identified the speech tokens less consistently. Thus, a severe history of OME appears to result in poorer phonetic processing, irrespective of language impairment. However, a combination of early OME experience and language impairment did not further increase the perceptual problems as indicated by the significant interaction between OME and Language Impairment, which suggests non-additivity for the levels of phonetic processing associated with OME and Language Impairment Finally, there was no significant interaction between OME and Stimulus Type, Language Impairment and Stimulus Type, and OME and Language Impairment and Stimulus Type ($F[1,40]=1.42$, $p=.241$; $F[1,40]=0.92$, $p=.342$; $F[1,40]=1.18$, $p=.283$, respectively). Thus, the processing of major and minor cues was largely similar for the control group and the three experimental groups.

With regard to the mean phoneme boundaries, there was a significant main effect of Language Impairment ($F[1,40]=4.76$, $p=.035$). The mean phoneme boundary of children with language im pairments was shifted to the right, which indicates a higher number of /b/ responses In addition, there was a significant main effect of Stimulus Type ($F[1,40]=4.54$, $p=.039$), which was the result of the subjects' tendency to perceive the voiced sounds from the conflicting continuum less ambiguously than the voiceless sounds in the conflicting-cues continuum.

## *Discrimination*

Discrimination results for each pair was expressed with the nonparametric estimate of d', yielding -ln eta scores (discriminability) and ln beta scores (response bias)

(Wood, 1976). The ln eta results, as a function of stimulus pair, are shown in Figures 4 6 and 4 7 for the cooperating-cues and the conflicting-cues continua, respectively Discriminability (-ln eta) equals zero when performance is at chance It increases with greater accuracy of discrimination, without influences of bias to respond "same" or "different " Discriminability is maximal at the value of ln eta of 4 6 This 4.6 value is obtained when the probabilities of correct "different" and correct "same" responses are both 99, which was the value assigned (for computational purposes) when the actual probabilities were 1 00

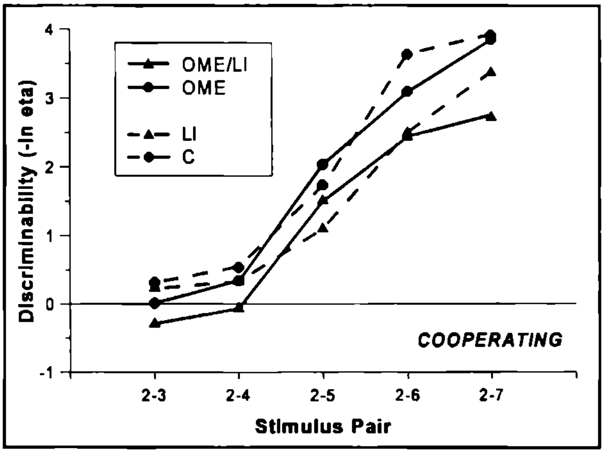



*FIGURE 4 6*
*Mean discrimination scores as a function of stimulus pair for the cooperating cues continuum*

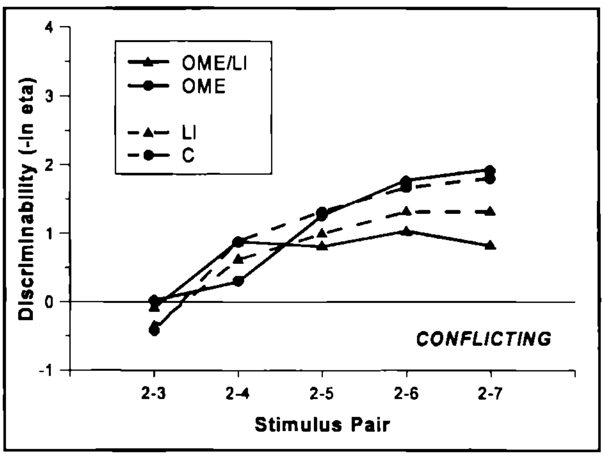



*FIGURE 4 7*
*Mean discrimination scores as a function of stimulus pair for the conflicting cues continuum*

From the overall level of the curve, it seems that the OME/LI group shows the poorest sensitivity of any of the groups in both Figure 4 6 and Figure 4.7. Especially in the conflicting-cues condition, this group has the shallowest discrimination function The Control group shows the steepest discrimination function in both the cooperating and the conflicting-cues condition This indicates highest sensitivity of all groups. The overall discrimination levels and the steepness of the functions of the OME group and the LI group seem to be within those of the OME/LI group and the Control group

A 3-way ANOVA (OME x Language Impairment x Stimulus Type) was performed on ln beta scores (response bias). This did not result in significant differences for either OME ($F$ [1,40]=0.55, $p$= 462), Language Impairment ($F$ [1,40]=0.23, $p$=.632), or OME x Language Impairment ($F$ [1,40]=1.11, $p$=.299) Hence, there were no differences in tendencies to favor one response over the other (independent of stimulus discriminability) between the groups.

We focused analyses on JND measures of sensitivity (We were interested in the sensitivity to voicing cues. JND measures sensitivity as a function of increasing physical differences between pairs As such, it reflects the smallest acoustical difference that can be heard.

In many studies on speech perception, overall discriminability is used as an index of discrimination. Overall discrimination is an average of the discriminability across all pairs (both within and across phoneme pairs). As a consequence, it is a less precise measure of sensitivity. In addition, using overall discrimination scores is most appropriate when working with a fixed-step AX discrimination task. We used an anchor procedure with variable stepsizes between pairs. A JND procedure is most appropriate in an anchor discrimination task. Therefore, our statistical analyses concern JND data only.) Linear regression analyses were performed on the individual discrimination functions. JNDs could be determined by computing the interpair difference that provided a discriminability of 50% of the maximum discriminability value (i.e , -ln eta = 2 3). Table 4 5 presents the mean JNDs for the four groups.

A 3-way ANOVA (OME x Language Impairment x Stimulus Type) of JNDs, with Stimulus Type as a repeated measure, resulted in significant effects of OME, Language Impairment, and Stimulus Type ($F$ [1,40]=4 39, $p$= 042; $F$ [1,40]=13.83, $p$<.001; $F$ [1,40]=55.51, $p$<.001, respectively). Children with early OME experience or language impairment required a greater auditory difference between two stimuli in order to differentiate between them. The significant Stimulus Type effect indicates that the cooperating-cues stimuli resulted in smaller JNDs than the conflicting-cues stimuli

**TABLE 4.5.**
Mean discrimination results for the four groups

| | JND | |
|---|---|---|
| | M | SD |
| **Cooperating cues** | | |
| OME/LI | 4 73 | 1.49 |
| OME | 4.02 | 0.65 |
| LI | 4 22 | 1.23 |
| Control | 3 33 | 0 75 |
| **Conflicting cues** | | |
| OME/LI | 7 63 | 0.78 |
| OME | 5.68 | 2 03 |
| LI | 6 04 | 1 72 |
| Control | 5 12 | 2.14 |

Note.
OME = history of Otitis Media with Effusion, LI = Language Impairment, JND = Just Noticeable Difference

Identification results from the current investigation, specifically slope results, suggest that children with early OME or language impairment have difficulties with categorization. The significant interaction between OME and Language Impairment demonstrates that co-existence of language impairment does not further deteriorate phonemic perception Further, discrimination results demonstrate that children with early OME, irrespective of language impairment, also have poorer sensitivity to voicing cues than children without early OME. Children with early OME or language impairment appear to need more redundancy of auditory information From the insignificant interaction terms OME x Stimulus Type and OME x Language Impairment x Stimulus Type on the JNDs, it can be deduced that the lower sensitivity is an overall effect and not particularly related to one or a few specific voicing cues.

Our results add new information to the results of Eimas and Clarkson (1986) and Clarkson et al (1989), who also used identification and discrimination tasks in assessing the long term effects of OME. However, they did not separate the contribution of language impairment from the contribution of early OME in a complete factorial design.

Eimas and Clarkson (1986) reported significant differences in overall discriminability (i e , averaged across pairs) that were due to OME In the current investigation, discrimination was assessed using JNDs instead of a fixed interval n-step AX discrimination task. From the correspondence across studies it can be deduced that the current discrimination procedure using the JND measure provided a sensitive means for assessing auditory processing of subtle acoustic differences.

However, unlike the present study, Eimas and Clarkson (1986) did not find that significant differences in identification were due only to OME. We found significant differences in phonetic identification that were due to both OME and language impairment It is likely that the use of both major and minor cues enhanced the sensitivity of the identification task to subject differences.

In addition, there are differences in design between the study of Clarkson et al. (1989) and our own. Clarkson et al studied 5-year-old children, we studied 9-year-olds Thus, maturational changes in the 4-year interval could have affected results differentially. We do partly agree with Eimas and Clarkson's (1986) interpretation of the results however. That is, recurrent OME may be considered a form of early sensory deprivation, and information relevant to the perception and categorization of speech may be less consistent during the years when the child should be acquiring the sound system of the native language. This inconsistency may aggravate discovery of how the specific structures of relevant acoustic information are mapped onto the sound categories of the language Furthermore, earlier OME episodes may be related to the currently observed poorer sensitivity of children with OME to voicing cues. Differing sensitivity may underlie their less-consistent phonetic identification abilities

The manipulation of conflicting and cooperating cues in the current study provided a means for studying potential differences in weighting of the major and minor cues to voicing in Dutch As shown in Table 4.4, all groups showed a higher phoneme boundary in the conflicting-cues condition as compared to the cooperating-cues condition. If the experimental groups attributed more weight to the minor cues, then one would expect their shift in phoneme boundary to be larger than that of the control group Although there was a tendency for the OME/LI group to make such a larger shift, it was not significant. We, therefore, conclude that the perceptual weighting of major and minor cues in the experimental groups is similar to the weighting in the control group.

Our factorial design provided the opportunity to study the effects of OME, irrespective of language impairment. Early OME is often accompanied by language impairment. An important question is whether language impairment can further interfere with auditory and phonetic processing when it coexists with early OME. Our results indicate that either early OME or language impairment is related to perceptual problems. A combination of the two, however, did not make speech perception significantly worse, although children with OME and language impairments did have the most shallow slopes in identification, the most shifted phoneme boundaries, and the poorest discrimination abilities of any group. Of course, the nonadditivity of the effects of OME and language impairment may be the result of a floor effect Thus, the nonadditivity of perceptual problems in cases of co-existence of a history of otologic problems and language impairment certainly is an interesting subject for future research.

Most psycholinguistic models of speech perception assume both auditory and phonetic levels in processing of speech. In a hierarchical dual-coding strategy (e.g., fitting the dual process model of Fujisaki & Kawashima, 1969, 1970), both processing stages show interdependency. Only in cases of insufficient information for phonemic decisions is acoustic information in memory consulted (see Macmillan, 1987). Classical dual-coding models of speech perception do not provide a rationale for independence of processing stages Earlier studies (Groenen, Maassen & Crul, 1994; Groenen, Maassen, Crul, & Hulsmans, 1994) suggest that discrimination and identification tap different perceptual processes. Auditory processing can be affected, whereas phonetic processing is intact. Although this was not the case in the current investigation, our results do fit a nonhierarchical structure of speech processing, involving an auditory stage and a phonetic stage partly allowing for stage-independent output, without the integrity of phonetic processing being dependent on the outcome of auditory processing.

In Groenen, Thoonen, Maassen, and Crul (1995) it was suggested that reduction of the redundancy in speech stimuli may increase their diagnostic value only when the reduction pertains to linguistically relevant dimensions. One of the criteria used in selecting the subjects for the present study was normal speech in-noise recognition Speech-in-noise tasks typically aim at assessing central perception The four groups employed in this study did not differ in their speech-in-noise recognition abilities whereas they did differ in our identification and discrimination tasks. This suggests that degradation of the stimuli with nonlinguistic information (e g., adding noise) may have less value for assessing psycholinguistic difficulties because of its marginal relationship to the speech signal and the specific processes of speech perception.

Research on the developmental sequelae of OME has been equivocal. The complex long-term effects of OME demand detailed attention to the different psycholinguistic levels of speech perception. The present study demonstrates that children with early OME experience (but normal hearing at present) show poorer sensitivity to voicing cues and less distinctive phonetic categorization, similar to children with language impairments (e.g., Thibodeau & Sussman, 1979). Disturbances in lower-level perception may have diverse effects on higher-order language learning processes. We suggest that these disturbances in lower-level perception processes form the basis for higher-order linguistic problems in some children and thereby form an intermediate between OME and the diversity of outcome in language learning.



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# Appendix

### *Factor Analyses on Questionnaires*

Principal factor analysis was used on each of two questionnaires (a questionnaire filled out by the children's parents and a questionnaire filled out by the children's teachers). This was done in order to obtain factor scores for linguistic competence Each questionnaire consisted of 36 items concerning speech, language and communication behavior. All items had three response alternatives. The exact contents of both questionnaires can be found in Grievink, Peters, van Bon, and Schilder (1993).

Principal factor analysis on the responses to the parent questionnaires yielded two orthogonal factors with considerable eigenvalues (greater than 2 0). We used a factor loading criterion of .65 to select relevant items. Factor 1 and factor 2 consisted of 11 and 0 items, respectively, with loadings above 65, and only the first factor was therefore used. The 11 items selected for factor 1 were best described in terms of general linguistic competence. To test for unidimensionality of the first factor, we repeated principal factor analysis on the 11 selected items This resulted in a first factor with an eigenvalue above 5.5 The remaining factors had eigenvalues below 1.0, which indicated unidimensionality for the selected items. For each child, factor scores were computed on the basis of the 11 items. Two examples of the 11 selected items are (a) "Has a faulty pronunciation in sentences," and (b) "Understands only simple sentences."

The same procedure was followed with the questionnaire filled out by the teachers. Principal factor analysis yielded two orthogonal factors with eigenvalues greater than 2.0. Factor 1 and factor 2 consisted of 16 and 3 items, respectively, with loadings above .65. Only the first factor was used As was the case with the questionnaire filled out by the parents, the 16 items selected for factor 1 were best described in terms of general linguistic competence. A repeated principal factor analysis on the selected 16 items resulted in a first factor with an eigenvalue above 9.0, whereas the remaining factors had eigenvalues below 1.0. This indicates unidimensionality of the selected items. Factor scores were computed on the basis of these 16 items. Two examples of the 16 selected items are (a) "Uses few different words," and (b) "Merely understands sentences consisting of very common and frequently heard words."

# THE SPECIFIC RELATION BETWEEN PERCEPTION AND PRODUCTION ERRORS FOR PLACE-OF-ARTICULATION IN DEVELOPMENTAL APRAXIA OF SPEECH

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## Abstract

Developmental apraxia of speech is a disorder of phonological and articulatory out put processes However, it has been suggested that perceptual deficits may contribute to the disorder Identification and discrimination tasks offer a fine grained assessment of central auditory and phonetic functions Seventeen children with developmental apraxia (mean age 8,9 years) and 16 control children (mean age 8,0 years) were administered tests of identification and discrimination of resynthesized and synthesized monosyllabic words differing in place of articulation of the initial voiced stop consonants The resynthetic and synthetic words differed in the intensity of the third formant, a variable potentially enlarging their clinical value The results of the identification task showed equal slopes for both subject groups, which indicates no phonetic processing deficit in developmental apraxia of speech The hypothesized effect of the manipulation of the intensity of the third formant of the stimuli was not substantiated However, the children with apraxia demonstrated poorer discrimination than the control children, which suggests affected auditory processing Furthermore, analyses of discrimination performance and articulation data per apraxic subject demonstrated a specific relation between the degree to which auditory processing is affected and the frequency of place-of articulation substitutions in production This indicates the interdependence of perception and production The results also suggest that the use of perceptual tasks has significant clinical value

# Introduction



The notion that developmental apraxia of speech (DAS) is a pathological syndrome has been abandoned (Guyette & Diedrich, 1981). Instead, DAS is considered to be a developmental disorder in the ability to perform purposeful speech movements (Hall, Jordan & Robin, 1993) The symptoms include frequent and inconsistent errors that are contextually constrained in the articulation of consonants and vowels (Crary, 1984; Crary, Landess, & Towne, 1984; Marquardt, Dunn, & Davis, 1985, MlCoch & Square, 1984; Stackhouse, 1992). However, the explanation of DAS as an output speech disorder does not preclude the possibility that most (but not all) children demonstrate additional language or language-related problems (Bridgeman & Snowling, 1988; Ekelman & Aram 1983; Hall et al., 1993; Marion, Sussman, & Marquardt, 1993; Snowling & Stackhouse, 1983).

In the present study, the relation between the perception and production of speech in the etiology and maintenance of DAS was examined. Several studies have demonstrated a relation between speech perception and articulatory deficits in diverse groups of subjects Hoffman, Daniloff, Bengoa, and Schuckers (1985) and Ohde and Sharf (1988) found that children with articulation problems had problems distinguishing /r/ from /w/ consistently. In addition, Monnin and Huntington (1974) found a specific relation between identification and production of /r/-/w/ contrasts in subjects with speech defects A specific relation between perception and production in children with articulation problems was also found by Raaymakers and Crul (1988) They studied the final /s-ts/ contrast Rvachew and Jamieson (1989) investigated the perception of fricatives in children with a functional articulation disorder. Their results suggested that for a subgroup of children with functional articulation disorders, production errors may reflect speech perception errors

Few studies have been conducted on perception and production skills in a specific group of children with developmental apraxia of speech. Hoit-Dalgaard, Murry, and Kopp (1983) studied voice onset time production and perception in subjects with apraxia. They found that children with apraxia had production as well as perceptual errors for the voicing feature. They did not, however, find a significant relationship between the two measures Marion et al (1993) found subjects with apraxia to have rhyming abilities inferior to those shown by control children. Hence, little is known about the relation between the perception and production of specific phonetic features in children with DAS.

According to Locke (1980a, 1980b), tests of perception with phonemes related to the specific articulation errors of the child may be particularly useful for the assessment of the relation between speech perception and production Thoonen, Maassen, Gabreels, and Schreuder (1994) identified a group of children with apraxia who specifically made errors on the initial consonantal place-of-articulation. For this reason, our primary interest in the present study is in the specific relation between the perception and production of place-of articulation for consonants in children with developmental apraxia of speech.

Data on the auditory perceptual skills of children with DAS are scarce (Hall et al., 1993). Guyette and Diedrich (1981) along with Edwards (1984) also explicitly mention the inconclusiveness of the available auditory findings This inconclusive ness may reflect the use of inappropriate or insensitive test procedures (Locke, 1980a) It may also reflect the lack of differentiation of speech perception into dis tinct processes

In the present study, a sufficiently sensitive test for the perception of speech was developed using speech sound continua A speech continuum consists of a series of speech tokens that vary acoustically for a single phonological contrast The redundancy of the speech signal used presently was reduced by focusing on acoustic cues for a single dimension (i e , the second and third formant transitions for cuing place of articulation) Important acoustic cues carrying place information are the transitions of the second and third formants and the spectrum of the relea se burst We decided to manipulate the formant transitions

Speech perception can be characterized by a series of processes including a preliminary auditory analysis, further auditory and phonetic feature analysis and the combination of phonetic features into a phonemic representation (Cutting & Pisoni, 1978, Pisoni & Sawusch, 1975) At any stage in this process, information can be placed in short-term memory Auditory processing includes a preliminary analysis and is related to auditory short term memory whereas phonetic processing includes phonemic labeling strategies and is related to phonetic memory (Baddeley, 1992) In order to distinguish the different processes in the auditory perception of speech, identification, and discrimination tasks were used

An identification task requires a phonemic judgment, and thus decisions are based primarily on the phonetic properties and features represented in phonetic short term memory The decisions involved in a discrimination task may be based on information from both phonetic and auditory memory (See Liberman, Harris, Hoffman, & Griffith, 1957, and Studdert Kennedy, Liberman, Harris, & Cooper, 1970, for the early studies on categorical perception )

A secondary interest in the present study is related to the differential effects of lowering the intensity of the third formant by using natural versus synthetic speech The structure of the third formant is viewed to be a minor cue for the Dutch place of articulation contrasts We wanted to compare the sensitivity of list eners to a reduction in the high frequency information of the signals, specifically to the minor cue for the b d dimension In our resynthesized natural speech all three formants (F1, F2, and F3) are well preserved, whereas in our synthetic speech the intensity of the third formant is decreased Huntress, Lee Creaghead, Wheeler, and Braverman (1990) found that aphasic subjects comprehended natural speech better than synthetic speech, particularly when the subjects first heard the synthetic speech More than half of the subjects in the study of Huntress et al demonstrated mild to severe apraxia of speech, and the authors did not compare the subjects to a control group Our synthetic stimuli may be more sensitive in the detection of per ception problems than natural stimuli, because of a lack of redundancy in the sign al and because there was lowered intensity in the third formant frequency Repp (1984) pointed to naturalness as a stimulus factor in normal speech perception and suggested that impoverished speech stimuli may impoverish perception Natural speech is more acoustically redundant than synthetic speech Thus, the question is whether children with apraxia need redundancy in the speech signal as in the cur rent investigation's "resynthesized" natural tokens. Furthermore, it was questioned whether lowering the intensity of the third formant of the synthetic tokens would differentially influence the perceptual behavior of the group with apraxia compared to the control group.

In Experiment 1, we focused on the perceptual abilities of a group with apraxia and a control group in response to a place-of-articulation continuum. Both the children with apraxia and the control children performed identification and discrimination tasks. In Experiment 2, the perceptual functions of the children with apraxia were compared to their specific articulatory behavior with a focus on place-of-articulation.



## Experiment 1

### Method

#### *Subjects*

The purpose was to form a homogeneous group of children whose main problem was apraxic in nature. The subjects with apraxia were 17 children (mean age 8;9 years, range 6;11 to 11;06 years) attending special schools for children with language and speech disorders in three Dutch cities.

In the pre-selection, information was obtained from medical and educational records; a speech evaluation had also been performed by the school speech-language pathologists. The criteria for DAS were derived from the characteristics mentioned in Hall (1992), Hall et al (1993) and Stackhouse (1992) The criteria for inclusion were: (a) high rates of speech sound errors; (b) inadequate diadochokinetic profile for the production of multisyllabic sequences (e.g., /pataka-pataka-pataka.../); (c) posturing and groping of the articulators; (d) periods of highly unintelligible speech, (e) difficulties with or inability to produce complex phonemic sequences; (f) high incidences of context-related sound substitutions (e.g , metathetic errors); and (g) an inconsistent speech performance. An inclusion criterion obtained from the medical and educational records was a slow development and remediation of speech skills.

In addition, information derived from the medical and educational records was used to determine exclusion criteria (see also Thoonen et al., 1994; Thoonen, Maassen, Wit, Gabreels, & Schreuder, 1995). This information indicated that each selected child (a) had no structural problems in the speech organs that could be held responsible for their speaking problems; (b) did not have otorhinolaryngologic problems; and (c) did not suffer from severe attention deficits. Each child with DAS functioned within a normal range of intelligence (IQ-range on standardized tests of intelligence was 84 to 108).

After the pre-selection, each child was tested during a short screening session This screening included: (a) imitation of pitch and temporal changes while sustaining the vowel /a/; (b) 10 minutes of spontaneous speech, and (c) imitation of eight short sentences. The first task (imitation of pitch and temporal changes) was used to determine whether the child could comprehend specific task instructions, and the latter two tasks were used to ascertain that each child had a complete phonemic repertoire

The final admission to the subject groups required the child to pass another phase of selection. Each child had to be unequivocally diagnosed by certified speech-language pathologists (Child Neurology Centre, University Hospital Nijmegen) as a clear case of DAS. Audio-taped recordings of spontaneous speech and sentence imitations were used for diagnostic classification. The speech-language pathologists had no access to the medical and educational records. The speech criteria used for the classification of DAS were identical to those used in the preselection by the school speech-language pathologists. Besides the category of developmental apraxia of speech, also classifications of dysarthria, dysphasia, functional articulation problem, and speech-language delay were made by the speech-language pathologists in a descriptive manner. Admission to the experimental DAS group required a perfect (100%) agreement between the two speech-language pathologists in categorizing the speech characteristics as moderate to severe symptoms of DAS.

The control subjects were 16 children (mean age 8;0 years, range 6;04 to 10;02 years) attending a regular elementary school. These children were recommended by their teachers. The children did not evidence learning disabilities, a history of hearing problems, speech and language problems, or speech-limiting structural abnormalities. Based on school performance and information from the classroom teachers, normal levels of cognitive, motoric, and perceptual functioning could be assumed. The control children were gender matched to those with DAS. These control children were in the same school grade as the children with apraxia, so the educational level was the same across groups. The mean age of the control subjects was slightly younger than that of the subjects with apraxia.

The children in both groups also met the following selection criteria: (a) absence of hearing loss on bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985); the maximally allowed hearing loss was 25 dB HL for either ear; (b) no previous exposure to resynthesized or synthesized speech; and (c) Dutch as the native language. In addition, only children who could correctly identify 11 out of a series of 12 words consisting of six random repetitions of two speech tokens representing the perceptually clearest ends of the speech continua (i.e., /bɑk/ and /dɑk/) were admitted to the study. The probability of obtaining 11 correct responses out of 12 trials based on chance alone was .003. The subjects had to pass this pretest so that we could exclude children who had difficulties accomodating to artificial speech. The pretest was administered prior to actual testing, and all of the 17 children with apraxia in the experimental group and 16 children in the control group passed the pretest.

### *Stimuli*

Two seven-step /b-d/ continua were generated. The first continuum was based on a natural adult male voice. By manipulation of the linear predictive coding parameters and resynthesis of the result, a "resynthetic" natural continuum was constructed. The starting point was utterance of the single word /bɑk/ (the Dutch word for *box*). After A/D conversion with a DASH-16 data-acquisition board (12 bit sampling at 10 kHz; band-pass filtering between 40 and 5000 Hz, low-pass cut-off frequency

5000 Hz with a decline of 60 dB/octave), the Interactive Laboratory System (ILS, V6.1, 1989) was used to manipulate the spectral structure of the initial formant transitions. Only the vowel portion (formant transitions plus steady-state vowel) was analyzed with pitch-synchronous linear predictive coding (covariance method: pre-emphasis factor .98, Hamming window), which yielded 12 reflection coefficients (Markel & Gray, 1976). The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients to autoregressive coefficients and then performing a fast Fourier transformation (FFT) The result was smoothed spectrally by interactively adjusting the formant frequencies.



**TABLE 5.1.**
Onset frequencies (in Hz) for the second and third formant transitions from the resynthetic and synthetic stimuli.

| Stimulus | F2 | F3 | |
|---|---|---|---|
| 1 | 1000 | 2150 | /bɑk/ |
| 2 | 1083 | 2317 | |
| 3 | 1167 | 2483 | |
| 4 | 1250 | 2650 | |
| 5 | 1333 | 2817 | |
| 6 | 1417 | 2983 | |
| 7 | 1500 | 3150 | /dɑk/ |

The consecutive stimuli of the resynthetic continuum ranged perceptually from /bɑk/ to /dɑk/ (i.e., the Dutch word for *roof*) and differed from one another in the starting value and slope of the transitions of the second and third formant. The onset frequencies of the F2 and F3 for each stimulus are shown in Table 5.1. F1 always started at 400 Hz. The transition of the first formant was 20 ms in duration. The transitions of the second and third formants were 52 ms in duration. All transitions were linear. The final 98 ms of the vowel consisted of steady-state formants appropriate for the Dutch vowel /ɑ/ with center frequencies at 750 Hz (F1), 1150 Hz (F2), and 2500 Hz (F3).

The sampled data were resynthesized with a pitch-synchronous synthesis procedure by transforming the manipulated reflection coefficients to inverse filter coefficients. Pitch period excitation used a unit pulse. The resynthesized vowel parts were spliced back into the original utterance /bɑk/, which produced seven stimuli ranging from /bɑk/ to /dɑk/. The total length of each stimulus was 381 ms, consisting of (a) voice-lead 71 ms; (b) burst 10 ms; (c) vowel /ɑ/ 150 ms, divided into 52 ms transition duration and 98 ms steady state; (d) silence interval (occlusion period /k/) 70 ms; and (e) release /k/ 80 ms. Stimulus phonemic quality was checked by having 10 adults label 10 repetitions of each of the seven stimuli presented in random order. The phoneme boundary was located for individual subjects between stimulus 3 and 5, indicating a valid choice of frequencies in the spectral manipulations

The second continuum was a "synthetic" /b-d/ continuum based on a text-to-speech system that followed the principles of allophonic synthesis. As in the resynthetic stimulus set, the consecutive stimuli of the synthetic continuum differed from one another in the starting value and slope of the transitions of the second and third formant (see Table 5.1).

The construction of the synthetic speech was intended to reduce the intensity of the third formant when compared to the resynthetic speech. This was accomplished by using the allophone-based text-to-speech system developed at the Institute of Phonetics, University of Nijmegen, The Netherlands. This system combines knowledge of the phonetic structure of phonemes with phonetic rules that adjust a phoneme's target values to its contextual surroundings (Boves, Kerkhoff, & Loman, 1987; Loman, Kerkhoff, & Boves, 1989). The linguistic component converts text to a phonemic representation supplemented by suprasegmental information about intonation, syllabic structure, and emphasis The phonetic component interprets the phonemic representation in terms of acoustic patterns, makes phonetic adjustments, and excitates a set of serial resonators. It is possible to change each of the parameters before actual synthesis. In order to make a reliable comparison between the resynthetic and the synthetic continuum, the synthetic stimuli were constructed using the temporal and spectral specifications for the resynthetic stimuli, which are linguistically relevant for the place-of-articulation contrast (formant transitions and vowel characteristics). The remaining parameters were determined using the rules of the system, resulting in minor spectral and temporal differences with regard to the resynthetic stimuli.

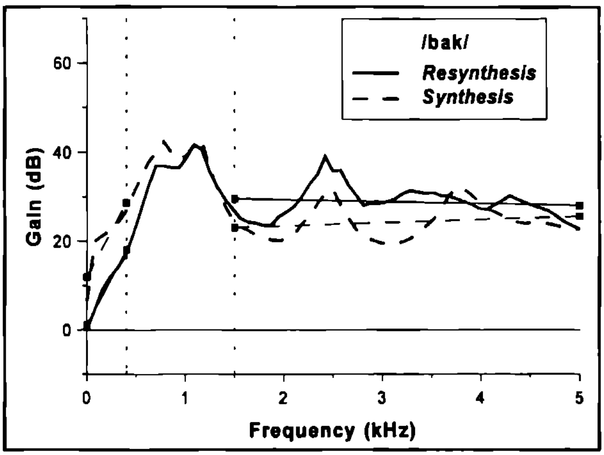



*FIGURE 5 1*
*Long-term average spectra of the resynthetic and synthetic endpoint tokens for /bɑk/ The non labeled lines represent overall intensity levels from 0 to 5000 Hz The lines labeled with squares represent the results of linear regression analyses on selected frequency regions*

The spectral structure of the synthetic and resynthetic speech was indicated by long term average spectra of the vowel part (formant transition and steady-state vowel). The vowel parts from both the resynthetic and synthetic endpoint tokens /bɑk/ and /dɑk/ were submitted to a series of 128 points FFTs (frame 12.8 ms, pre-emphasis .98, Hamming window). Long-term average spectra were computed by averaging the intensity levels in each frequency band over time. Figures 5.1 and 5.2 present the long-term average spectra of the endpoint tokens for /bɑk/ and /dɑk/, respectively. The most important information from the high and low frequencies in the long-term average spectra can be extracted by modifying two of the five indices originally proposed by Hammarberg, Fritzell, Gauffin, Sundberg, and Wedin (1980). The two indices concern the slope of the spectral envelope (a) below 400 Hz, and (b) between 1 5 and 5 kHz. In the present study, we were not interested in the slope value but in the overall frequency level indicated by the intercept (*a*) in the regression function. In Figures 5.1 and 5.2, the lines labeled with squares represent the results of linear regression analyses on the selected frequency regions.

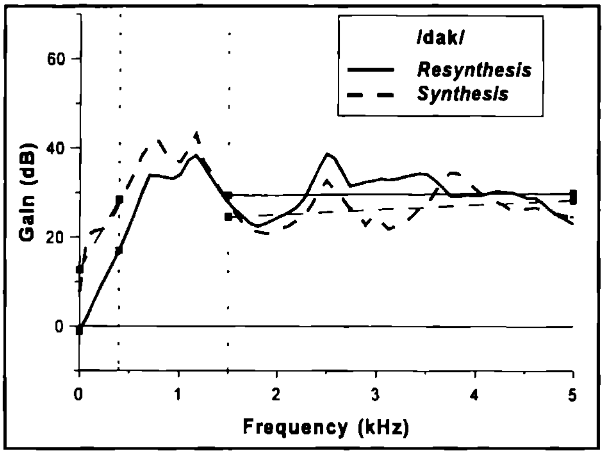



*FIGURE 5 2*
*Long-term average spectra of the resynthetic and synthetic endpoint tokens for /dɑk/ The non-labeled lines represent overall intensity levels from 0 to 5000 Hz The lines labeled with squares represent the results of linear regression analyses on selected frequency regions*

In the frequencies below 400 Hz, the synthetic speech has a higher intensity than the resynthetic speech In the frequencies above 1500 Hz, the resynthetic speech has a higher intensity than the synthetic speech. For both continua, frequencies of the third formant were well within the spectral range after 1500 Hz, whereas frequencies of the second formant were within the spectral range before 1500 Hz. Thus, the resynthetic stimuli showed pronounced third formant amplitude, whereas the synthetic stimuli showed decreased intensity levels of the third formant, confirming the validity of our experimental manipulation

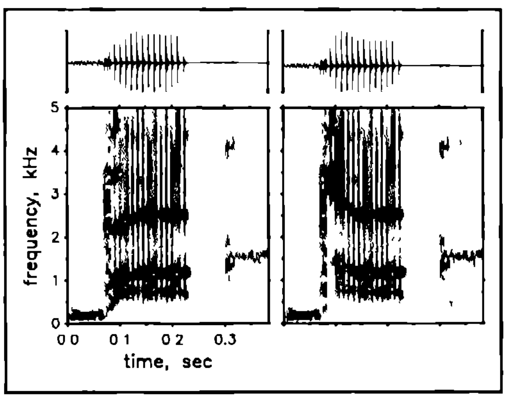



*FIGURE 5 3*
*Waveform and spectrogram of the resynthetic endpoint tokens /bɑk/ (left panel) and /dɑk/ (right panel)*

The synthetic and resynthetic stimulus sets were comparable with regard to the spectral cues for place-of-articulation. As a result of different systems for stimulus generation, there were minor acoustic differences between the resynthetic and the

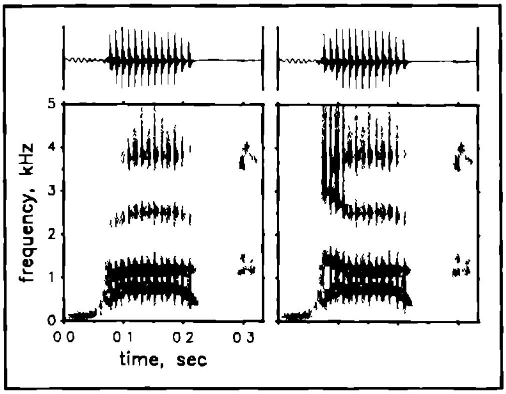



*FIGURE 5 4 Waveform and spectro gram of the synthetic endpoint tokens /bɑk/ (left panel) and /dɑk/ (right panel)*



synthetic speech (voice-lead. 71 ms - 65 ms; occlusion /k/: 70 ms - 75 ms; release /k/: 80 ms - 30 ms; duration F1-transition: 20 ms - 25 ms, duration F2/F3-transition· 52 ms - 50 ms, total length stimulus. 381 ms - 330 ms, respectively). Hence, these differences did not influence the perception of the feature place-of-articulation In Figures 5.3 and 5.4, the oscillograms and spectrograms displaying the endpoint tokens for /bɑk/ and /dɑk/ when resynthesized and synthesized are presented.

### *Procedure*

The stimuli were recorded and played back using an Ampex 467 DAT-tape on a Grundig Fine Arts Digital Audio Tape recorder (type DAT-9000: 16 bit D/A converter, 2-fold oversampling, sampling frequency 48 kHz) Presentation was via a Beyerdynamic closed headphone (Type DT770) The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL) Subjects were tested in a quiet room

Each subject was examined twice within a two-day period. In order to get accustomed to the artificial speech, the subject first listened to six repetitions of each of the four endpoint stimuli. The subject then had to identify 11 out of a series of 12 endpoint stimuli correctly for both the resynthetic and the synthetic speech (see subject selection criteria). After this, the subject was administered the main experimental tasks two identification and two discrimination tasks. The two synthesized stimuli tasks (identification and discrimination) and the two resynthesized stimuli tasks (identification and discrimination) were presented together, with the order counterbalanced across subjects over the two days. The discrimination and identification tasks for one stimulus set was presented on the same day.

The identification task was based on a two-alternative forced choice response procedure and consisted of 10 repetitions of each of the seven stimuli presented in a random order in five series of 14 stimuli. The stimuli were separated by an interstimulus interval of 5000 ms. The subjects could identify the stimulus by pointing to one of two pictures: a picture of a box, representing the stimulus /bɑk/, or a picture of a roof, representing the stimulus /dɑk/. Half of the subjects began with the resynthetic stimuli while the other half began with the synthetic stimuli The children were encouraged to respond but never received differential feedback for particular responses

The discrimination tasks consisted of same-different (AX) judgments for resynthetic and synthetic stimulus pairs In order to obtain a bias-free measure of discriminability, the discrimination tasks were set up in such a way that signal detection analysis could be applied (Coombs, Dawes, & Tversky, 1970). For this, each task contained physically different as well as identical pairs In both the resynthetic and synthetic discrimination tasks, the subjects were presented three series of 15 stimulus pairs. Each series consisted of one identical pair for each of the seven stimuli, one physically different pair for each of the five possible 2-step comparisons (1-3, 2 4, 3-5, 4-6, 5-7), and one physically different pair for three 3-step comparisons (2-5, 3-6, 4-7). The latter were treated as dummies explicitly intended to elicit "different" responses. In each series, the pairs were randomly ordered with an intrapair interstimulus interval of 600 ms and an interpair interval of 5000 ms. The subjects were required to point to one of two pictures after hearing a pair of stimuli· a picture of a triangle and a circle, representing the concept "different", or a picture of two circles, representing the concept "same". Half of the subjects began with the resynthetic stimuli while the other half began with the synthetic stimuli.

## Results

### *Identification*

In Figure 5.5, the mean identification curves for the children with apraxia and the control children for the resynthetic and the synthetic stimuli are presented. Each individual identification curve was submitted to probit transformations (Finney, 1971). The probit method determines the value of the phoneme boundary and slope by iteratively computing the cumulative normal distribution that comes closest to the data, using a maximum likelihood criterion. The resulting distribution has a mean (i.e., the interpolated 50% crossover point or phoneme boundary) and a standard deviation (i.e., a measure of the variability of scores around the mean). The slope is the reciprocal of the standard deviation and indicates the range of uncertainty in distinguishing one phoneme category from another. A high slope value indicates a small uncertainty range and suggests a highly consistent ability to categorize a speech contrast whereas a low slope value indicates a large range of uncertainty and suggests difficulties in identifying the speech stimuli. In Table 5.2, the mean phoneme boundary and slope scores for the apraxic and the control groups are presented.

A two-factor analysis of variance (unbalanced design) was used to test for differences in the scores. The two factors were Group (apraxic versus control) and Stimulus Type (resynthesis versus synthesis) with the levels of the latter factor treated as repeated measures

A significant difference in the slopes for the resynthetic and synthetic continua ($F$ [1,31]=8.38, $p$<.01) with a higher score on the resynthetic variant was found. The range of uncertainty was increased by the use of synthetic stimuli The mean slope for the group with apraxia did not differ significantly from the mean slope for the control group ($F$ [1,31]=0.02, $p$=.89), showing that the children with apraxia performed as consistently as the control children.

**TABLE 5 2**
Mean identification results for the children with apraxia and control children on the resynthetic and synthetic stimuli

| | Phoneme boundary | Slope |
|---|---|---|
| **Apraxic** | | |
| Resynthesis | 3 871 | 2 843 |
| Synthesis | 4 240 | 1 997 |
| **Control** | | |
| Resynthesis | 4 196 | 2 667 |
| Synthesis | 4 573 | 2 102 |

A significant interaction between Group and Stimulus Type also was not found ($F$ [1,31]=0 33, $p$= 57), indicating that the synthetic stimuli did not improve our ability to distinguish children with apraxia from control children

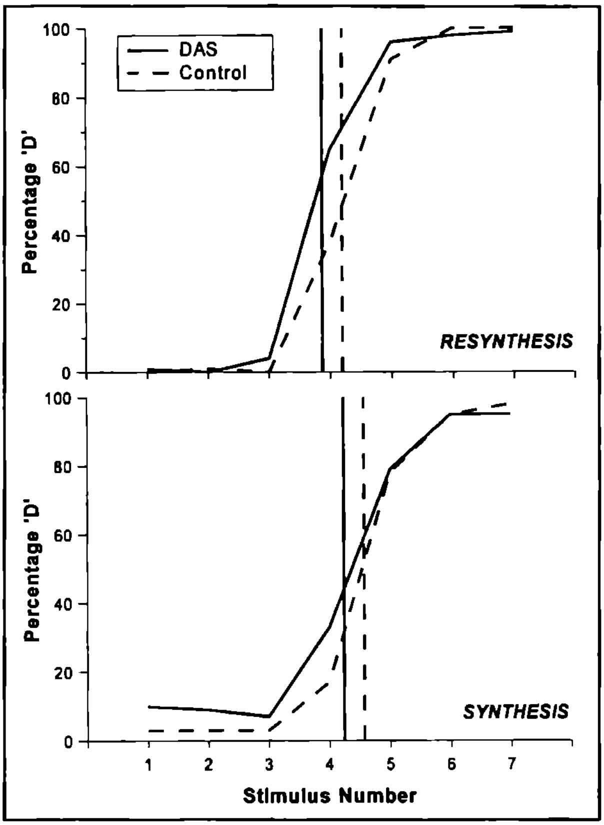


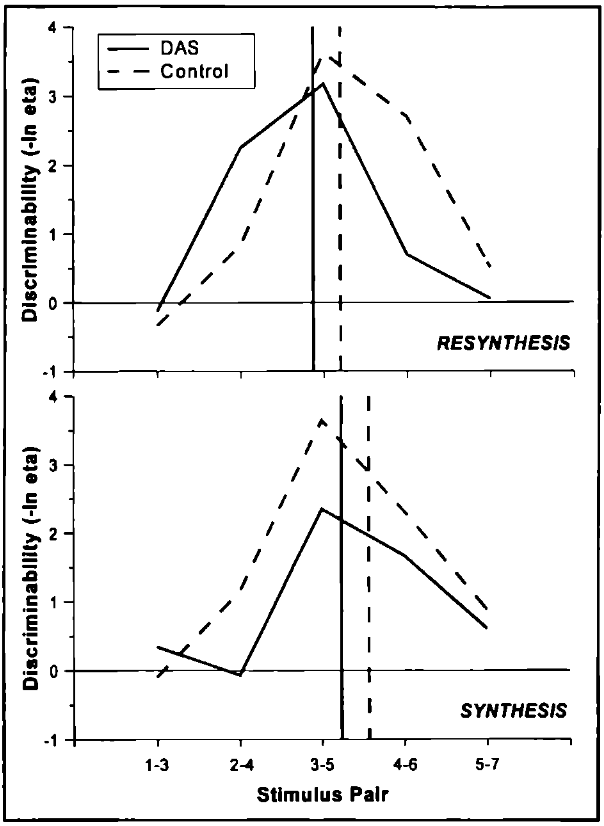

*FIGURE 5 5*
*Mean percentages D responses as a function of stimulus number for the children with apraxia (DAS) and control children in the resynthetic condition (top panel) and the synthetic condition (bottom panel) Vertical lines indicate the location of the mean phoneme boundary*

The phoneme boundary for the group with apraxia compared to the control group was significantly shifted to the left ($F$ [1,31]=6 68, $p$< 05) Children with developmental apraxia demonstrated a bias for the perception of /d/ The phoneme boundary for the resynthetic continuum when compared to the synthetic continuum was also shifted to the left ($F$ [1,31]=10.72, $p$<.01). Subjects identified resynthetic more than synthetic stimuli as /d/. The latter effect was independent of Group, as indicated by the lack of an interaction between Group and Stimulus Type ($F$ [1,31]=0.00, $p$= 9725).

### *Discrimination*

The discrimination functions, which plot the discriminability of each 2-step pair in terms of a nonparametric estimate of d' (-ln eta, Wood, 1976) as a function of stimulus pair, are shown in Figure 5.6 for the resynthetic and synthetic pairs, respectively. Discriminability equals zero when performance is at chance It increases with increasing discrimination accuracy without influences of bias to respond "same" or "different". Discriminability is maximal at the -ln eta value of 4.6; this value is obtained when the probabilities for the correct "difference" and correct "same" responses are both .99, the value assigned (for computational purposes) when the actual probabilities were 1.00.

*FIGURE 5 6 Mean discrimination scores as a function of stimulus pair for the children with apraxia and control children in the resynthetic condition (top panel) and the synthetic condition (bottom panel) Vertical lines indicate the location of the mean phoneme boundary*




A multivariate analysis of variance on the discriminability data (MANOVA, Group x Stimulus Type, statistic: Wilks' lambda) revealed a significant effect of Group ($F$ [5,27]=2.8623, $p$<.05). The mean discrimination pattern for the children with apraxia was different from that of the control children. In addition, there was a Stimulus Type difference ($F$ [5,27]=2.7625, $p$<.05) indicating differential treatment of the resynthetic versus synthetic stimulus pairs The extent of the stimulus type difference was, moreover, dependent on Group (interaction Group and Stimulus Type $F[5,27]=3\ 7261$ $p< 05$)

In order to specify the general effects in the MANOVA, a 3 way ANOVA (Group x Stimulus Type x Stimulus Pair) with repeated measures on Stimulus Type and Stimulus Pair was performed Identification results demonstrated that the mean phoneme boundary for the children with apraxia was shifted to the left Shifts in the mean discrimination peak, as a mere result of shifts in phonemic identification, were confirmed by the significant Group x Stimulus Pair interaction ($F[4,124]=4\ 69$, $p< 01$) In addition, and more interesting, the significant differences between the children with apraxia and control children (results MANOVA) could be accounted for by their overall discrimination levels the children with apraxia performed more poorly ($F[1,31]=4\ 44$, $p< 05$) Using synthetic speech did not produce a different pattern of responses for the two groups (no significant Group x Stimulus Type interaction, $F[1,31]=1,50$, $p= 22$)

The children with apraxia demonstrated the same amount of uncertainty on perceptual categorization in the region of the phoneme boundary as the control children This suggests that phonetic processing was not affected and that the poorer overall discrimination performance of the children with apraxia is the result of deficient auditory processing



## Discussion

The results of Experiment 1 showed children with apraxia to have equally steep identification slopes when compared to control children, indicating equally consistent phonetic processing across groups The mean phoneme boundary for the group with apraxia is shifted to the left when compared to the control group, suggesting that for this group the stage where acoustical properties are combined to form a phonemic judgment may be biased towards the alveolar variant However, the extent to which the phoneme boundary is shifted never exceeds one stimulus on the stimulus dimension, explaining the lack of dramatic identification problems

Perceptual differences between children with apraxia and control children were indicated by the significant differences in their discrimination scores The children with apraxia demonstrated poorer discrimination than the control children, which indicates poorer auditory processing Children with apraxia appear to have less access to information in auditory memory than children without apraxia

Intensity of the third formant (resynthesis versus synthesis) was found to influence both identification and discrimination The identification and discrimination performance of both groups was poorer on synthetic than on resynthetic stimuli However, the spectrally degraded synthetic stimuli hardly affected the performance of the children with apraxia more than the performance of the control children, which suggests insignificant clinical value This finding complements those of Huntress et al (1990) for aphasic subjects An instant effect of synthetic speech was found along with improved speech comprehension by the aphasics with practice The aphasic performance was not compared to that of a control group, however, so little could be said about the clinical value of the synthetic speech used in their study

Reducing the intensity of the third formant in the synthetic speech tokens can be viewed as a reduction of the redundancy of the speech signal. The manipulation of intensity does not affect the integrity of the transiental character of the fomants, and as such does not degrade aspects of the signal with high cue value for establishing the phonemic contrast. It can be concluded that this reduction of the redundancy of the speech stimulus in our study does not increase its clinical value or the sensitivity of perception tasks. Lowering the intensity of the third formant with the use of degraded synthetic speech may simply not tap into central auditory problems because of the potentially marginal relation to the speech signal and the specific processes of speech perception. Inducing overall spectral poorness (in the present study by lowering the intensity of the third formant) thus appears to have little value for the assessment of central auditory problems In contrast, a reduction of the stimulus redundancy by using speech continua appears to have clinical value. This method of reduction pertains to dimensions that directly concern features essential for speech recognition (i.e., formant transitions in the perception of place-of-articulation contrasts) and therefore appears to have a direct effect on the process of speech perception.

## Experiment 2

In Experiment 2, the hypothesis regarding a relation between the speech-processing deficit in the children with apraxia and specific problems with regard to the production of place-of-articulation information was tested.

### Method

#### *Subjects*

The subjects were the same 17 children with apraxia as in Experiment 1.

#### *Materials*

Two articulation tests of 30 words and 36 pseudowords (see Appendix A for contents) were used in this experiment Apart from semantics, the tests using real words had a higher phonemic complexity and a higher complexity of syllabic structure. The tests were previously used in a study of verbal apraxic articulatory behavior by Thoonen et al. (1994).

#### *Procedure*

Each subject was asked to imitate 30 single words and 36 single pseudowords. The repetitions were recorded by tape recorder and phonetically transcribed (IPA) by three certified speech-language pathologists

#### *Analysis*

To assess the reliability of the phonetic transcriptions, an interjudge agreement analysis was carried out across the total set of 66 words (30 words and 36 pseudowords) for three randomly selected children with developmental apraxia of speech and three of the children with normal speech The latter children were matched for age and gender to the three children with apraxia. The prime transcriber and two additional transcribers, each fully acquainted with the procedures of IPA transcription, transcribed a total of 1542 consonants in 428 utterances (mean of 3.9 consonants per utterance) The Pearson correlation coefficients across the judges for the total number of one-feature errors (place, manner, and voicing) and multiple-feature errors per subject were between .92 and .99 ($p<.05$).

The transcriptions of the consonants in particular were then analyzed and transferred into confusion matrices. In matrices for each target feature (place, manner, and voice), the percentage of substituted consonants that were correct with respect to that particular feature (but in error with respect to one or both of the other features) was calculated. The "percentage feature retention" was tabulated for each target feature, and --within each feature-- for each value of the feature (e.g., target feature· place; values. bilabial, labiodental, alveolar, palatal, velar, glottal).

Five scores for place-of-articulation were then derived to represent each child's performance. (a) The proportion "one feature" place-substitutions (e.g., target: /p/, realization. /t/) was calculated across the total number of initial syllabic consonants for words and for (b) pseudowords. (c) The proportion "multiple feature" place-substitutions including place-manner (e.g., target /p/, realization: /s/), place-voice (e.g., target: /p/, realization: /d/), and place-manner-voice (e.g., target: /p/, realization /l/) was calculated across the total number of initial syllabic consonants for words and for (d) pseudowords Finally, (e) the mean proportion place-substitutions across all words and pseudowords (i.e., the number of "one-feature" place-substitutions and "multiple feature" place-substitutions divided by the total number of consonants in the words and pseudowords) was calculated. In order to determine the specificity between place perception and place production, we also calculated these five production scores for manner-of-articulation and voicing.

**TABLE 5.3.**
Means and standard deviations for the production and perception scores for the children with apraxia.

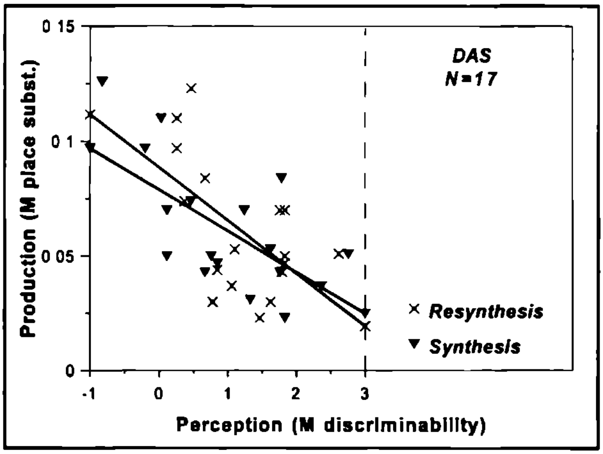
| | Mean | Standard Deviation |
|---|---|---|
| **Production (proportion place substitutions)** | | |
| "One Feature" | | |
| words | 058 | .064 |
| pseudowords | 082 | 029 |
| "Multiple Feature" | | |
| words | .045 | .041 |
| pseudowords | .054 | .027 |
| Mean Proportion | 061 | .029 |
| **Perception (Mean Discriminability)** | | |
| Resynthesis | 1.210 | 0.697 |
| Synthesis | 0.981 | 0 976 |

Experiment 1 had shown the children with apraxia to discriminate the place contrast less well than the control children. The production scores for place-of-articulation were therefore compared to the mean discriminability of the resynthetic stimuli and the synthetic stimuli in order to examine the specific relation between perception and production.

## Results

In Table 5.3, the mean scores for the five production measures and two perception measures for the children with apraxia are presented.

*FIGURE 5.7. Scatterplot of the individual perception and production scores for place-of articulation Regression lines are included for both the resynthetic and synthetic conditions*




In Figure 5.7, the mean discriminability for place-of-articulation is plotted against the mean proportion place substitutions per subject for both the resynthetic and synthetic conditions. Cross-correlation of the production variables with the perception variables produced the Pearson product-moment correlation coefficients as listed in Table 5.4. If perception is related to production (i.e., high mean discriminability level and low proportion place-substitutions), then the correlations should be significantly negative.

The mean discriminability scores for the resynthetic and synthetic conditions were negatively related to the mean proportion place substitutions ($r=-.56$, $p<.05$ and $r=-.61$, $p<.01$, respectively). The mean discriminability of the resynthetic condition was negatively related to the proportion "one feature" place-substitutions for both words and pseudowords ($r=-.49$, $p<.05$ and $r=-.54$, $p<.05$, respectively). The mean discriminability of the synthetic condition was negatively related to the proportions of "multiple feature" place-substitutions for both words and pseudowords ($r=-.50$, $p<.05$ and $r=-.64$, $p<.01$, respectively). In addition, the synthetic condition was negatively related to the proportion "one feature" place-substitutions in words ($r=-.49$, $p<.05$). There were no significant correlations between the perception scores and production substitutions for the manner-of-articulation or voicing.

The correlation coefficients revealed a specific relation between place perception and place production. In order to examine the utility of this relation for the diagnosis of children with apraxia, the relation between the perception and production scores for only the poorest performers was examined. Those children with moderate to severe developmental apraxia of speech were selected out of the group of 17 children with apraxia. This selection was based on the perception as well as the production data and produced a number of different subject subsets. The overlap between these subsets was then examined to determine the number of children who performed particularly poorly on both perception and production.

**TABLE 5.4.**
Pearson product moment correlation coefficients for the five production measures with the two perception measures for place, manner, and voicing. $^{*}p< 05$, $^{**}p<.01$

| | Proportion Substitutions | | | | |
|---|---|---|---|---|---|
| | "One Feature" | | "Multiple Feature" | | Mean |
| | words | pseudo | words | pseudo | Proportion |
| **Place subst.** | | | | | |
| **Mean Discriminability Place** | | | | | |
| Resynth | -.49* | - 54* | - 36 | 27 | - 56* |
| Synthesis | - 49* | - 22 | - 50* | - 64** | - 61** |
| **Manner subst.** | | | | | |
| **Mean Discriminability Place** | | | | | |
| Resynth | 31 | - 32 | - 07 | .12 | - 14 |
| Synthesis | 22 | -.46 | - 03 | - 21 | - 39 |
| **Voicing subst.** | | | | | |
| **Mean Discriminability Place** | | | | | |
| Resynth | - 00 | 33 | - 01 | - 09 | 21 |
| Synthesis | - 19 | .29 | 27 | - 22 | .15 |

An objective division based on the number of place substitutions was made. Randomization testing (Edgington, 1987) was used to nonparametrically single out the poorest performing cases with apraxia. Exhaustive randomization testing was performed on the four proportion measures for place-substitutions (the mean total proportion place-substitutions was excluded), and all of the possible solutions for the selection of a subgroup of six children were tested. This randomization test resulted in six poorest performing subjects with apraxia (the test statistic used was equivalent to *F* for MANOVA, see details of the selection process in Appendix B).

In selecting the poorest performing cases with apraxia on perceptual grounds, the mean discriminability of (1) the resynthetic stimuli and (2) the synthetic stimuli were taken into consideration. For each of the two measures, the six children with the poorest scores were selected for comparison.

Comparison of the different poorest performing subsets produced overlap frequencies of 5 for both the resynthetic and the synthetic condition. From the six poorest performing subjects in perception, five were included in the six poorest performing subjects in production.

The significance levels for the overlap were calculated using the following formula:

$$p = \frac{\binom{S}{O} * \binom{N-S}{S-O}}{\binom{N}{S}}$$

where

**N** = Total number of children with apraxia (=17)

**S** = Number of children in selection (=6)

**O** = Number of matches (=5)

and binomial coefficients, e.g.:

$$\binom{S}{O} \frac{S!}{O!(S-O)!}$$

where

**S!** = 1*2*3*. .*(S-1)*S

etcetera

If *O*>=5 (i.e., at least five matches), the cumulative *p* is .005 This indicates an *O*-value significantly higher than that expected with random selection.

Comparison of the subsets based on the perceptual discriminability scores and the subsets based on the randomization testing procedure for production produced a significant number of matches for both the resynthesis and synthesis conditions. In addition, of the five matches in the resynthetic conditions, four were included in the five matches in the synthetic condition, which indicates the reliability of the perceptual tasks.

The results of the poorest performing subset comparisons emphasize the relation between problems in perception and problems in production. The overlap between the poorest performing subjects in perception and the poorest performing subjects in production was found to be large, which strongly indicates the clinical value of the discrimination tasks.

## Discussion

In Experiment 2, the specific relation between the perception and production of place-of-articulation was studied. A feature-to-feature comparison was undertaken The degree of disturbance of place discrimination was found to be closely related to the number of place substitutions in speech production with no relation between place discrimination and manner or voicing substitutions in production. This supports the feature-specific interdependence of perception and production The clinical significance of this interdependence was also demonstrated by comparing the poorest performing subjects in production to the poorest performing subjects in perception, which resulted in a significant number of matches. In addition, the results of our experiment cross-validate the methods used to assess perception and production

## General Discussion

At the theoretical level, our results pose some interesting problems. According to a dual-coding structure of auditory and phonetic processing, it is difficult for auditory discrimination to be disturbed while phonetic identification is normal. That is, dual-coding models of speech perception as described in Sawusch and Nusbaum (1983) and Sawusch and Mullenix (1985) do not provide a clear rationale for this phenomenon The question, then, is whether or not consistent phonetic identification can develop with problems of auditory processing? One can assume task or stimulus factors to be a possible explanation for our results, but these were ruled out in the present study One cannot question the materials (e.g., the use of ecologically invalid stimuli) or the procedure (e.g., the use of "same/different" tasks). Rather, a substantial, feature specific, perceptual component in developmental apraxia of speech appears to exist. This means that the validity of classical models of speech perception should be questioned. A better mapping process from the acoustic to phonetic stages seems needed, one which may depend on language exposure. Because discrimination performance was affected while identification consistency was not, the results of our study support a structure for speech processing with an auditory stage and a phonetic stage partly allowing for stage-independent output and the integrity of phonetic processing not being totally dependent on the outcome of auditory processing. This view is supported in a theoretical note from Ades (1977) on the perception of speech and nonspeech. He suggests the possibility of phonetic processing not receiving input from acoustical traces and instead forming an entirely independent route.

Another explanation for the incongruity of our findings with a hierarchical model of speech perception could lie in subject strategy factors If the dysfunctional auditory profile of children with developmental apraxia of speech is assumed to be a reflection of the application of an abnormal discriminative strategy, then it is not unlikely that the auditory dysfunction may be the result of selective attention. Nittrouer and Studdert-Kennedy (1987) and Nittrouer (1992) demonstrated that children show different cue weighting strategies than adults. In studies on the perception of syllable-initial fricatives, it was shown that preschool and young school aged children weighted intrasyllabic formant transitions more than adults did in making phonetic decisions. Dysfunctional auditory processing, then, may be determined by the process of attributing different (yet valid and adequate) weights to acoustic cues in the process of categorization (phonetic processing) as compared to the cues on which auditory discrimination was based. This would allow discrimination performance to be affected while phonetic identification was not (one of the results of this study). Such a viewpoint is highly compatible with the fuzzy logical model of speech perception from Massaro (1987, 1992). This viewpoint also seems compatible with the concepts of the WRAPSA model (Word Recognition and Phonetic Structure Acquisition) of Jusczyk (1993) According to Jusczyk, preliminary auditory analysis reflects the inherent organization of the human auditory system The auditory analyzers belong to the innate endowment of the infant After the development of a weighting scheme, language-specific phonetic decisions can be made. Selective attention within a set of intraphonetic cues, then, seems likely to play a role in phonetic processing It is possible that for children with DAS, cues playing a minor role are weighted less in phonetic processing Thus, problems with auditory processing of these minor cues may not have as much importance for phonetic processing as might problems in discrimination of more important speech cues such as the second formant transition for perception of place-of-articulation.

An interesting issue in trying to understand developmental apraxia of speech is whether the underlying dysfunction should be sought at the level of output motor processes or at the level of phonological representations. Marion et al. (1993) found children with apraxia to have inferior rhyming abilities to those of children without apraxia. They suggest a conceptualization of DAS as a fundamental disorder of the segmental phonological level of language that influences all relevant language components. Just as interesting as the etiology of DAS and perhaps related, is the potential value of perceptual tasks in the differentiation of psycholinguistic pathologies. Using tasks similar to those in the present study, Sussman (1993) found children with language impairments to show poorer phonetic categorization than children without language impairments. Her results support hypotheses from Gathercole and Baddeley (1990) suggesting that the phonological component of working memory may be disordered in children with language impairment. Should developmental apraxia of speech be a dysfunction at an output motor level, then there may be a specific symptomatology associated with the dysfunction and different from that for children with language impairment We, indeed, found children with apraxia to have problems in discrimination (i.e., auditory processing) and not in phonetic categorization A straightforward conclusion is that perceptual tasks have differential clinical value. Moreover, our results appear to be incompatible with an explanation at the level of phonological representation and appear to favor the conception of DAS as a senso-motoric problem (see MlCoch & Square, 1984).

A different and difficult problem arises in the determination of the causal connection between perception and production. Studies of normal perception and production skills have shown many instances of perception preceding production. In reviewing the potential causal relation between perception and production, Strange and Broen (1980) point out that human infants appear to be sensitive to acoustic-phonetic dimensions that allow them to perceive phoneme contrasts far in advance of any ability to produce such contrasts. Kuhl (1991) has shown that phonetic category prototypes exist at an age of six months, serving as language-specific "perceptual magnets" for other stimuli Her results have led to the development of the Native Language Magnet (NLM) theory which describes how innate factors along with experience with a specific language form the development of speech perception (Kuhl, 1993). The earlier mentioned WRAPSA model (Jusczyk, 1993) assumes the emphasis on the critical dimensions needed for distinguishing among words in the native language to be developed during the second half of the first year of life Whereas the WRAPSA (Jusczyk, 1993) and the NLM (Kuhl, 1993) differ in emphasis on lexical/phonological contrast and phonetic categories, respectively, both theories suggest that during the first year of life, prior to the time that infants acquire word meaning and contrastive phonology and prior to the critical time for the development of production skills, essential phonetic perception strategies have been developed. In keeping with this view, Rvachew and Jamieson (1989) report that certain speech perception deficits may in fact contribute to articulation disorders.

In addition to the idea that perception precedes production, however, there are also signs that production can affect perception (Crul, 1990; Monnin & Huntington, 1974) Hoffman et al. (1985) hypothesize that children with certain articulation problems may not experience enough communicative pressure to develop the critical phonological contrasts in sufficient phonetic detail. Their productive neutralization may then lead them to ignore the contrast perceptually as well.

The present data do not address the causal relation between perception and production directly. It is likely that the relevant phonological processes in perception and production interact. The presumed neurological defect that initially disrupted the oral motor functioning of the child may also have disrupted the auditory functioning of the child at the same time. In any case: the present study clearly shows that auditory perception of children with developmental apraxia is affected, and this fact must be considered not only in the diagnosis of developmental apraxia of speech but also in the development of a valid course of therapy.



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# Appendix A
## *Contents of lists used to test articulatory skills*

*List 1 Words (30 items)*

1 nijmegen
2 diploma
3 pyjama
4 limonade
5 meenemen
6 liniaal
7 portemonee
8 paraplu
9 lokomotief
10 paddestoel
11 fopspeen
12 fietstas
13 kokskind
14 kapstok
15 nepski
16 tikspel
17 kletskous
18 prikstok
19 hutspot
20 viltstift
21 koekoeksklok
22 voetbalwedstrijd
23 kleurpotlood
24 bladzijde
25 spiksplinternieuw
26 tandpasta
27 gereedschapkist
28 hartstikkestoer
29 bliksemflits
30 brandweerspuit

*List 2 Pseudowords (36 items)*

1 pabata
2 faxaga
3 ladata
4 katada
5 nalama
6 bapama
7 bakaba
8 saxata
9 tanada
10 bapaka
11 xatasa
12 dalata
13 tadaka
14 xafaka
15 mabapa
16 pataba
17 lanama
18 tadana
19 pata
20 bapa
21 lada
22 xafa
23 tada
24 kaxa
25 nama
26 bapa
27 lana
28 daba
29 data
30 nala
31 paka
32 paba
33 sata
34 safa
35 nada
36 tada

# Appendix B
## *Randomization test*

Randomization testing (see Edgington, 1987) is intended to determine nonparametrically the probability value associated with a given comparison. The statistic used to test the difference between the two functions is:

$$\sum_{j=1}^{s} \sum_{i=1}^{k} \mathbf{T}_{ij}^{2} / \mathbf{N}_{i}$$

where

$\mathbf{T}_{ij}$ = total score of group *i* and variable *j*
$\mathbf{N}_{i}$ = number of subjects in group *i*
**k** = number of groups being compared (in our case 2)
**s** = number of variables (in our case 4)

The resulting test statistic is equivalent to the $F$ of MANOVA. The probability value associated with the computed test statistic is determined by randomization test as follows The data from the subjects in the groups being compared are repeatedly divided into groups. The data for each subject consist of the vector of scores on each variable. The vectors are permuted as a unit. The test statistic is computed for each of 1,000 randomly selected permutations. The probability value is the proportion of the test statistics equal to or greater than the test statistic obtained from the actual division of subjects into groups.

Increasing $F$s reflect increasing differences between groups. In the present study, we wanted to select the seven poorest performing subjects based on four variables. In other words, we wanted a division into groups with the largest possible test statistic. This subgroup of seven could be computed by performing randomization tests on the four variables. In order to make an exhaustive search for the best division, the number of permutations was not fixed to 1,000. Our program tested all possible solutions for selecting a subgroup of 6 out of 17 children (12,376 permutations) The division associated with the highest test statistic consisted of the six poorest performing subjects.

# AUDITORY AND PHONETIC PERCEPTION OF VOWELS IN CHILDREN WITH APRAXIC SPEECH DISORDERS

*Paul Groenen, Thom Crul, Ben Maassen*

## Abstract

The explanation of articulatory problems as an output speech disorder does not preclude the possibility that children may demonstrate additional language or language-related problems. Auditory and phonetic processing of vowels in the etiology and maintenance of apraxic speech disorders was examined. Stimulus specifications were chosen as to eliminate perceptual redundancy by moving the formants to a "neutral-vowel position". Two vowel continua, /ι/-/I/ and /a/-/α/, were used for identification and discrimination tasks. The subjects with apraxic speech problems were 11 children (mean age 8:0 years, range 6:11 to 9:6 years). The group of children with apraxic speech problems demonstrated poorer perception of vowels than the control children for both the /ι/-/I/ and the /a/-/α/ condition. Identification functions indicated poorer phonetic processing. The children with apraxic speech problems also demonstrated poorer discrimination than the control children. Children with apraxic speech problems demonstrated a need for perceptual redundancy and required a greater acoustic difference between two stimuli in order to perceptually differentiate between them than control children This indicated poorer auditory processing. The articulation-disordered children showed a high amount of interindividual variation for both identification and discrimination. Subgroups with similar atypical perception patterns could be established. A combination of perception measures (identification and discrimination) proved to have a high differential and clinical value for the assessment of children with apraxic speech problems.

Apraxic speech disorders are considered a developmental disorder in the ability to perform purposeful speech movements (Hall, Jordan & Robin, 1993) The symptoms include frequent and inconsistent errors that are contextually constrained in the articulation of speech sounds (Crary, 1984, Crary, Landess, & Towne, 1984 Marquardt, Dunn, & Davis, 1985, MlCoch & Square, 1984, Stackhouse, 1992) Since articulation defects form a large proportion of the disorders in speech pathology (Monnin & Huntington, 1974), for the development of therapy it is vital to get fundamental insight in the etiology and symptoms of the disorder

The explanation of articulatory problems as an output speech disorder does not preclude the possibility that children may demonstrate related language problems (Bridgeman & Snowling, 1988, Ekelman & Aram 1983, Groenen, Maassen, Crul, & Thoonen, 1996b, Hall, Jordan, & Robin, 1993, Marion, Sussman, & Marquardt, 1993, Snowling & Stackhouse, 1983) In the present study, the perception of speech sounds in the etiology and maintenance of apraxic speech disorders was examined

The relation between perception and production is well established Several studies have demonstrated a specific relation between consonant perception and articulatory deficits in diverse groups of subjects (Hoffman, Daniloff, Bengoa, & Schuckers 1985, Ohde & Sharf, 1988, and Monnin & Huntington, 1974, for the /r/ /w/ distinction, Broen, Strange, Doyle & Heller 1983, for /w/ /r/, /w/ /l/, and /r/ /l/ contrasts, Raaymakers & Crul, 1988, for the final /s ts/ contrast, Rvachew & Jamieson, 1989, for fricatives) Output speech disorders are often accompanied by perception problems

Few studies have been conducted on perception and production skills in a specific group of children with apraxic speech disorders Hoit Dalgaard, Murry and Kopp (1983) studied voice onset time production and perception in subjects with developmental apraxia of speech They found that children with apraxia had production and perception errors for the voicing feature Marion et al (1993) found subjects with apraxia to have rhyming abilities inferior to those shown by control children Groenen et al (1996b) found children with developmental apraxia of speech to have problems in auditory processing of place of articulation features

Data on the auditory perceptual skills of children with apraxic speech problems are scarce (Hall et al , 1993) Guyette and Diedrich (1981) along with Edwards (1984) explicitly mention the inconclusiveness of the available auditory findings This inconclusiveness may reflect the lack of differentiation of speech perception into distinct processes In the present study, the quality of speech perception in children with apraxic speech problems was studied on a phonetic and an auditory processing level

Speech perception can be characterized by a sequence of processes, including a preliminary auditory analysis, further auditory and phonetic feature analysis, and the combination of phonetic features into a phonemic representation (Cutting & Pisoni, 1978, Pisoni & Sawusch, 1975) Different properties of auditory and phonetic modes of perception were confirmed by Mann and Liberman (1983) At any stage in the process of speech perception, information can be placed in short term memory Auditory processing includes a preliminary analysis and is related to audi tory short-term memory whereas phonetic processing includes phonemic labelling strategies and is related to phonetic memory (Baddeley, 1992). In the present study, an attempt was made to distinguish between the different processes in the perception of speech. This was accomplished by administering identification and discrimination tasks. An identification task requires a phonemic judgment, and thus decisions are based primarily on the phonetic properties and features represented in phonetic short-term memory. In a discrimination task, however, not only phonetic information is used but the listener can also base perceptual judgments on information in auditory memory (see Liberman, Harris, Hoffman, & Griffith, 1957; and Studdert-Kennedy, Liberman, Harris, & Cooper, 1970, for the early studies on categorical speech perception) The importance of auditory and phonetic processing abilities for the development of language has been studied in children with normally developing language (e.g., Nittrouer & Studdert-Kennedy, 1987; Sussman, 1993a) and in children with language impairments (e.g , Groenen , Crul, Maassen, & Van Bon, 1996a; Sussman, 1993b; Tallal & Piercy, 1974, 1975).

Groenen et al. (1996b) and Groenen, Maassen, Crul, and Hulsmans (1994) showed that children with developmental apraxia of speech and developmental dyslexia showed auditory processing problems. They found that speech perception problems easier manifested themselves in auditory processing than in phonetic processing. A straightforward and seemingly logical conclusion could be that these children did not have problems in phonetic processing However, an alternate explanation could be that the type of stimulus (consonants) had a too high identifiability and speech cues were perceptually too salient. Whereas consonants showed to cover part of the dynamics of speech processing, vowels could well prove to be useful in covering different areas of speech processing, sensitively assessing specific problems of central auditory processing.

Whereas consonant misarticulations in children with apraxic speech problems have been reported extensively, there is also evidence that vowel misarticulations play a role in the etiology of apraxic speech problems. Odell, McNeil, Rosenbek, and Hunter (1991) and Canter, Trost, and Burns (1985) showed apraxic children not only to make errors in consonant production but also in vowel production. Pollack and Hall (1991) and Walton and Pollack (1993) systematically described vowel misarticulation in children with developmental apraxia of speech. Perceptual transcription and acoustic analyses demonstrated patterns of diphthong reduction, laxing, tensing, and derhotacization. According to Locke (1980), tests of perception with phonemes related to the specific articulation errors of the child may be particularly useful for the assessment of the relation between speech perception and production. Vowel misarticulations are associated with apraxic speech problems. This validates taking vowels as auditory stimuli for the assessment of speech perception

For perception, differences in categoricalness between consonants and vowels are hypothesized to derive from the different strengths of their representations in auditory memory. Repp (1984) mentioned that, "One might think of auditory and phonetic decisions being engaged in a race, with auditory decisions winning when the stimuli are isolated vowels but losing when the stimuli are stop consonants " Allophonic variations of vowels are easier to discriminate than those of consonants. The perception of vowels tends to be based more on the sensory characteristics of the acoustic information than on an abstract perceptual category (Crowder, 1981) The acoustic specifications of vowels are considered less highly 'encoded" than those of stop consonants (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967, Schouten & van Hessen, 1992) In general, vowels are less categorically perceived compared to consonants The sensitivity of both identification and discrimination tasks may be enhanced by utilizing vowels instead of consonants in the assessment of speech perception problems Therefore, we chose for using vowels instead of consonants

To further sensitize testing of speech perception processes, in the present study speech sound continua were utilized A speech continuum consists of a series of speech tokens that vary acoustically for a single phonological contrast The redundancy of the speech signal was reduced by focusing on acoustic cues for a single dimension To sensitively assess phonetic processing, stimuli were chosen with relatively low identifiability There are differences between vowels and consonants in the acoustic features that act as cues for perception Since the major acoustic cues for vowels are the steady state frequencies of the first three formants, formant frequencies were manipulated

Besides reducing the redundancy of the speech material by using continua, another procedure to reduce the redundancy of the speech tokens was followed which was based on the variability of the acoustic correlates of vowels in different speech conditions The acoustic correlates of isolated vowels can be regarded as stemming from an ideal articulatory position Rakerd (1984) argued that given the infrequency of its occurrence in natural speech, an isolated form can be considered an unrepresentative variant of a vowel The acoustic correlates of a vowel can vary substantially depending on the context in which it is spoken Formant frequency values of vowels are systematically perturbed by consonantal context (Nearey, 1989) In normal conversation, canonical ideal acoustic and articulatory vowel targets are often not reached Strange (1989) mentioned that the degree of discrepancy from the target formant frequencies is dependent on phonetic context, stress, rate of speech, and individual differences in coarticulatory strategies Fourakis (1991) specified this by demonstrating that vowel reduction and shrinkage of the overall vowel space seem to be dependent on different factors Context seemed to have an effect on phonetic vowel reduction, whereas stress and tempo affected the overall vowel space Koopmans van Beinum (1980) showed that vowel reduction across different speaking conditions was characterised by the deviation in the acoustic vowel space from an ideal position towards a central point Shearme and Holmes (1962) called this central point the "neutral-vowel position" or schwa /ə/ To sensitively assess speech perception processes, in the present study, vowel stimuli were chosen with a low level of redundancy, that is, vowels that approached the 'neutral vowel position" while preserving vowel identity and ecological realism

Experiment 1 was performed as a study to determine the specific stimulus settings needed for the stimulus material in Experiment 2 We focused on the effect of reducing vowel contrasts on phonetic perception in adults with normal hearing Vowel specifications were chosen as to eliminate perceptual redundancy by moving the formants to a 'neutral vowel position " In Experiment 2, the perceptual abilities of a group of articulation disordered children and a control group of children in response to two vowel continua were studied. The two continua, /i/-/I/ and /a/-/α/, covered a major part of the vowel space defined by the first three formants Both the children with articulation problems and the control children were administered identification and discrimination tasks.

The main questions were: (a) do children with apraxic speech problems exhibit problems in the perception of vowels? (b) are potential speech perception problems of phonetic or auditory origin?



## Experiment 1

Vowel reduction is considered the deviation in the acoustic vowel space from an ideal position towards a central point. The ideal positions are supposed to be those vowel positions that provide the greatest acoustic contrasts (vowels spoken in isolation). Shearme and Holmes (1962) found a large displacement towards the "neutral-vowel position" for the formant frequencies of vowels in a text read aloud compared to vowels in isolated monosyllables.

Koopmans van Beinum (1980) studied vowels spoken in different contexts: (a) vowels in isolation; (b) vowels spoken in isolated monosyllabic words; (c) vowels in stressed position in a text read aloud; (d) vowels in unstressed position in a text read aloud; (e) vowels in stressed position in a retold story; (f) vowels in unstressed position in a retold story; (g) vowels in stressed position in normal conversation; and (h) vowels in unstressed position in normal conversation. Increasing vowel contrast reduction was found from isolated vowels to free conversation Generally, vowels in unstressed position in speech conditions with free choice of words (retold story and free conversation) demonstrated the greatest centralization towards the "neutral-vowel position" or, in her study, the speaker centroid. For perception, vowels spoken in isolation showed very high identifiability scores, whereas vowels taken from normal conversation showed low identifiability scores.

Shifting towards the speaker centroid was found to reflect different speaking conditions Therefore, it ecologically validated the construction of sensitive stimulus materials Of interest, then, was the amount of centralization needed for phonetic perception of vowels to deteriorate In the present experiment, the effect of reducing vowel contrasts on phonetic perception in adults with normal hearing was studied.

### Method

#### *Subjects*

The subjects were five Dutch adults (three male, two female, mean age 28:11 years, range 22:6 to 31:2 years) with normal hearing. None of the subjects had structural problems in the speech organs or otorhinolaryngologic problems. The subjects did not show hearing loss, as tested by bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985); the maximally allowed hearing loss was 20 dB HL for either ear The subjects had never been exposed to computer-manipulated speech. For all subjects, Dutch was the native language.

### *Stimuli*

Four speech series, each consisting of eight speech tokens with variable frequencies of F1, F2, and F3 were generated. The series differed in vowel identity (/i/, /I/, /a/, and /α/) To degrade vowel cues, the spectral characteristics of a "neutral-vowel position" had to be determined. This was done by analyzing five natural male utterances of each of 12 Dutch monophthongs (/i/, /I/, /e/, /ε/, /a/, /α/, /ɔ/, /o/, /u/, /y/, /ø/ and /œ/) spoken in isolation, and computing the centroid for this specific speaker. After A/D conversion (16 bit sampling at 10 kHz; low-pass filtering at 5000 Hz), the Computerized Speech Lab (CSL Model 4300, V5.05) was used for analyzing the spectral structure of the speech tokens. Steady-state vowel parts of 400 ms were submitted to a series of 128 points FFTs (frame 12.8 ms, pre-emphasis .98, Hamming window). Long term average spectra were computed by averaging the intensity levels in each frequency band over time. Formant frequencies were derived from the peaks in the long-term average spectrum per vowel In Figure 6.1a, the frequencies of the first and second formant are displayed for all vowels. The formant values were in accordance with values found by Pols, Tromp, and Plomp (1973) in a study on frequency aspects of Dutch vowels from 50 male speakers. To compute the speaker centroid, the grand average across all vowels was computed (Figure 6.1b). The speaker centroid served as the reference position for determining the specific areas of vowel degradation. These areas are presented in Figure 6.1c. Next, the average vowel was assigned the number 1. The distances from average vowel (/i/, /I/, /a/, or /α/) to the speaker centroid was divided into 10 equidistant steps. Eight out of the 10 levels of vowel reduction were selected for the present study (see Figure 6.1d).

The LPC Parameter Manipulation/Synthesis Program (ASL Model 4304, V1) was used for manipulating and resynthesizing the spectral structure of the signal. For each vowel, one utterance was analyzed using a pitch-asynchronous autocorrelation method (pre-emphasis factor: .95, Hamming window, frame length: 150 points, filter order: 12), see Markel & Gray (1976) for details on LPC The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients to autoregressive coefficients and then performing a fast Fourier transformation (FFT) For each of the four vowels, the frequencies of F1, F2, and F3 were reduced towards the speaker centroid in eight steps as displayed in Figure 6.1d. This resulted in four series of eight speech tokens (i.e., a total of 32 stimuli). Sampled data were resynthesized with a pitch-asynchronous synthesis procedure by transforming the manipulated reflection coefficients to inverse filter coefficients The total length of each stimulus was cut back to 200 ms, a value proven to be typical for isolated vowels in speech production (Koopmans-van Beinum, 1980) and to preserve the speechlike aspects of the vowel (see Repp, 1984). Artificial clicks were avoided by cutting at zero-crossings at the beginning of a glottal period.

### Procedure

The stimuli were recorded and played back using an Ampex 467 DAT-tape on a Grundig Fine Arts Digital Audio Tape recorder (type DAT-9000. 16 bit D/A converter, 2-fold oversampling, sampling frequency 48 kHz). Presentation was via a Beyerdynamic closed headphone (Type DT770) The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL). Subjects were tested in a quiet room.

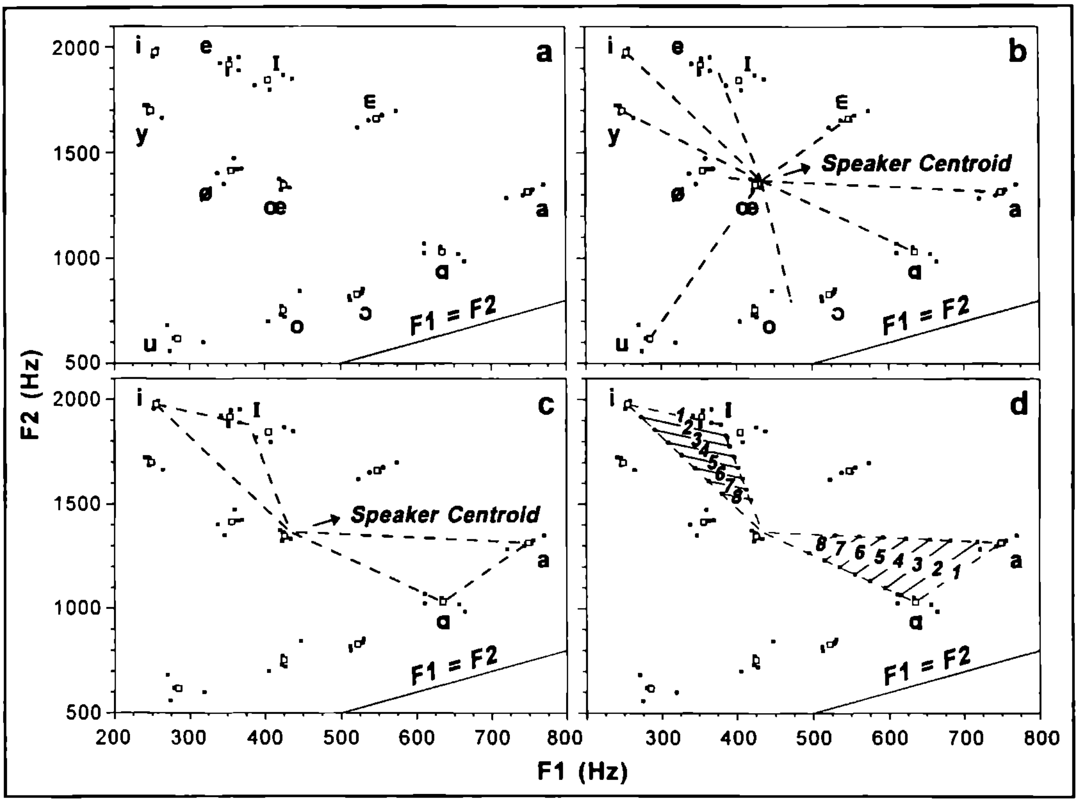



*FIGURE 6 1*
*Stimulus construction for Experiment 1 (a) Two dimensional vowel space based on F1 and F2, (b) Determination of the speaker centroid, (c) Frequency areas for vowel degradation for /i/, /I/, /a/ and /ɑ/, (d) Representation of eight levels of vowel degradation Hollow squares indicate average positions per vowel*

Each subject was examined once in a session of about 20 minutes To get accustomed to the artificial speech, the subject first listened to four repetitions of each of the four perceptually clearest stimuli with F1, F2, and F3 frequencies taken from the average vowel. The identification task was based on a five-alternative forced choice procedure and consisted of five repetitions of each of the 32 speech tokens presented in a random order in five series of 32 stimuli The stimuli were separated by interstimulus intervals of 3000 ms. The subjects could identify the initial phoneme of the stimulus by marking the appropriate space (/i/, /I/, /a/, /α/, and /œ/) on a form specially designed for this purpose Adding response alternative /œ/ was justified by the fact that the speaker centroid came very close to the characteristics of the vowel /œ/ (see Figure 6.1b) and therefore provided a plausible response possibility.



**TABLE 6.1.**
Confusion matrix for the perception of degraded vowels in adults with normal hearing

| | level vowel reduction[1] | i | I | a | α | œ | % error |
|---|---|---|---|---|---|---|---|
| i | 1 | 25 | - | - | - | - | 0 |
| | 2 | 24 | 1 | | - | - | 4 |
| | 3 | 25 | | - | | | 0 |
| | 4 | 21 | 4 | - | - | - | 16 |
| | 5 | 6 | 19 | - | - | - | 76 |
| | 6 | 3 | 22 | - | - | - | 88 |
| | 7 | 0 | 25 | - | - | - | 100 |
| | 8 | 0 | 18 | - | - | 7 | 100 |
| I | 1 | - | 25 | - | - | - | 0 |
| | 2 | | 25 | - | - | - | 0 |
| | 3 | - | 25 | - | - | - | 0 |
| | 4 | - | 25 | - | - | - | 0 |
| | 5 | - | 25 | - | | | 0 |
| | 6 | - | 22 | - | | 3 | 12 |
| | 7 | - | 13 | - | - | 12 | 48 |
| | 8 | | 9 | - | | 16 | 64 |
| a | 1 | - | - | 25 | - | - | 0 |
| | 2 | - | - | 23 | 2 | - | 8 |
| | 3 | - | | 24 | 1 | - | 4 |
| | 4 | | - | 23 | 2 | - | 8 |
| | 5 | - | | 15 | 7 | 3 | 40 |
| | 6 | | - | 12 | 5 | 8 | 52 |
| | 7 | - | - | 7 | 6 | 12 | 72 |
| | 8 | - | - | 1 | 3 | 21 | 96 |
| α | 1 | - | | 1 | 24 | - | 4 |
| | 2 | | - | - | 25 | - | 0 |
| | 3 | - | - | - | 25 | - | 0 |
| | 4 | - | - | - | 23 | 2 | 8 |
| | 5 | - | - | - | 21 | 4 | 16 |
| | 6 | - | - | 1 | 10 | 14 | 60 |
| | 7 | - | - | - | 10 | 15 | 60 |
| | 8 | - | - | 1 | 1 | 23 | 96 |

Note 1
The levels of vowel reduction correspond to the numbers displayed in Figure 6 1d)

# Results

In Table 6 1, the confusion matrix for the perception of degraded vowels in adults with normal hearing is presented The perception of the speech token /i/ rapidly changed to /I/ when the vowel reduction exceeded level 4 The perception of the vowel /I/ changed to /œ/ with vowel reduction levels greater than 6 This seemed a logical consequence of moving towards /œ/ without 'passing' other vowels in the vowel space The perception of stimuli stemming from /a/ seemed to change to /ɑ/ and /œ/ as a function of the nearest mean vowel neighbour Finally, the perception of the vowel /ɑ/ showed shifting towards /œ/ when the reduction level exceeded 5 Similarly to the /I/ condition, this seemed to be a consequence of moving towards /œ/ without entering other vowel areas In general, perceptual phonemic confusions seemed to be directly related to euclidean distances in the vowel space determined by F1 and F2

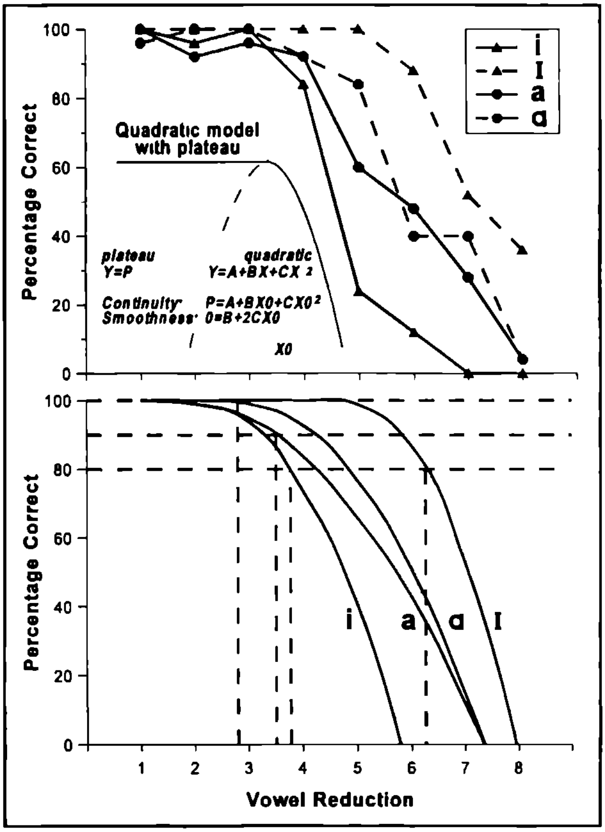



*FIGURE 6 2*
*Identification curves (top) and regression lines (bottom) for the four vowels as a function of vowel reduction On the vertical axis the percentages correctly perceived are displayed*

In Figure 6 2 (top), the mean percentages "correctly perceived vowel' are presented for /i/, /I/, /a/, and /ɑ/ Nonlinear regression lines were estimated by applying a segmented model a quadratic model with a plateau (SAS Institute Inc , 1985) The regression procedure estimated the perceptual breakpoint (X0) and the degree of curving For values greater than X0, the equation relating the level of vowel reduction and percentage correctly perceived vowel' was a parabola, whereas for values less than X0, the equation was a horizontal line There were two restrictions (a) the curve had to be continuous (the two sections had to meet at X0), and (b) the curve had to be smooth (the first derivatives with respect to the level of vowel reduction had to be the same at X0)

In Figure 6.2 (bottom), the regression lines for /i/, /I/, /a/, and /α/ are presented. For Experiment 2, endpoint tokens for the /i/-/I/ and the /a/-/α/ continuum were needed, consisting of vowel stimuli that were sufficiently critical to sensitively assess central auditory speech perception processes The choice of formant frequencies of these endpoint tokens was based on the vowel retention functions as approached with nonlinear regression

The endpoint tokens of the continua were chosen by taking vowel stimuli with formant frequencies that elicited above 75% correct responses in children with normal hearing. For this, stimulus phonemic quality was determined by having five children with normal hearing (mean age 9·5 years, range 8.6 to 10:3 years ) label a set of perceptually degraded vowel stimuli which successively elicited 80%, 90% and 100% correct responses in adults with normal hearing (see Figure 6.2, top) The criterion of 75% correct responses was met at vowel reduction levels as indicated by dashed lines in Figure 6.2 (bottom) The formant frequencies associated with these critical levels were considered most sensitive and taken as composing the spectral structure of the endpoint tokens of the continua used in Experiment 2.



## Experiment 2

The perceptual abilities of a group of articulation-disordered children and a control group of children in response to a sensitized /i/-/I/ and /a/-/α/ continuum were studied Both the children with articulation problems and the control children were administered identification and discrimination tasks. Since it was not certain wether or not children with articulation problems formed a homogeneous group with regard to speech perception, group as well as individual data were evaluated. In addition, perceptual subgrouping and the clinical value of perceptual measures were evaluated.

### Method

#### *Subjects*

The purpose was to form a homogeneous group of children whose main articulation problem was apraxic in nature. The subjects with apraxic speech problems were 11 children (mean age 8:0 years, range 6 11 to 9.6 years) attending special schools for children with language and speech disorders in a Dutch city.

In the preselection, information was obtained from medical and educational records and a speech evaluation by the school speech-language pathologists. The criteria for apraxic speech problems were derived from the characteristics mentioned in Hall (1992), Hall et al. (1993) and Stackhouse (1992). The criteria for inclusion were. (a) high rates of speech sound errors, (b) inadequate diadochokinetic profile for the production of multisyllabic sequences; (c) posturing and groping of the articulators, (d) periods of highly unintelligible speech; (e) difficulties with or inability to produce complex phonemic sequences; (f) high incidences of context-related sound substitutions (e.g., metathetic errors), and (g) an inconsistent speech performance. An inclusion criterion obtained from the medical and educational records was a slow development and remediation of speech skills.

In addition, each child had to be unequivocally diagnosed by certified speech-language pathologists as having apraxic speech problems. This diagnosis was made through classification based on spontaneous speech production and speech and sentence imitations. Besides the category of articulation problems of apraxic nature also classifications of dysarthria, functional articulation problems, and language delay were made by the speech-language pathologists. Admission to the experimental group required categorizing the speech characteristics as moderate to severe symptoms of apraxic speech problems.

Information derived from the medical and educational records was used to determine exclusion criteria (see also Groenen et al, 1996b; Thoonen et al , 1994) This information indicated that each selected child (a) had no structural problems in the speech organs that could be held responsible for their speaking problems, (b) did not have otorhinolaryngologic problems; and (c) did not suffer from severe attention deficits. Each articulation-disordered child functioned within a normal range of intelligence (performance IQ on standardized tests of intelligence was above 85, WISC-R, Wechsler, 1986)

The control children were 12 subjects (mean age 8;1 years, range 7:0 to 9.8 years) attending a regular elementary school. These children were recommended by their teachers. The children did not evidence learning disabilities, a history of hearing problems, speech and language problems, or speech-limiting structural abnormalities Based on school performance and information from the classroom teachers, normal levels of cognitive, motoric, and perceptual functioning could be assumed The control children were gender matched to the young children with articulation problems and were in the same school grade, so the educational level was the same across groups

The children in both groups also met the following selection criteria: (a) absence of hearing loss on bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985); the maximally allowed hearing loss was 25 dB HL for either ear, (b) no previous exposure to resynthesized speech, and (c) Dutch as the native language.

### *Stimuli: Generating the two continua*

Stimulus specifications were based on results of Experiment 1 In Experiment 1, the redundancy of the speech tokens was reduced by shifting formant frequencies towards the speaker centroid. In the present experiment, the redundancy of the speech tokens was additionally reduced by shifting the formant frequencies from one sensitized vowel to the other. Two 7-step vowel continua were generated: (a) an /i/-/I/ continuum, and (b) an /a/-/ɑ/ continuum. In Figure 6.3, the /i/-/I/ and /a/-/ɑ/ continuum is plotted in the vowel space determined by the first two formants In Table 6.2, the frequencies for the first, second and third formant of the vowel stimuli for both continua are presented The consecutive stimuli were generated, as in Experiment 1, through manipulation of the linear predictive coding parameters and resynthesis of the results The duration of each stimulus was 200 ms In Figure 6 4, the waveforms and spectrograms for the endpoint tokens of both continua are displayed.

*FIGURE 6 3*
*Representation of two optimally sensitive vowel continua (/i/ /I/ and /a/ /ɑ/) in the vowel space determined by F1 and F2*

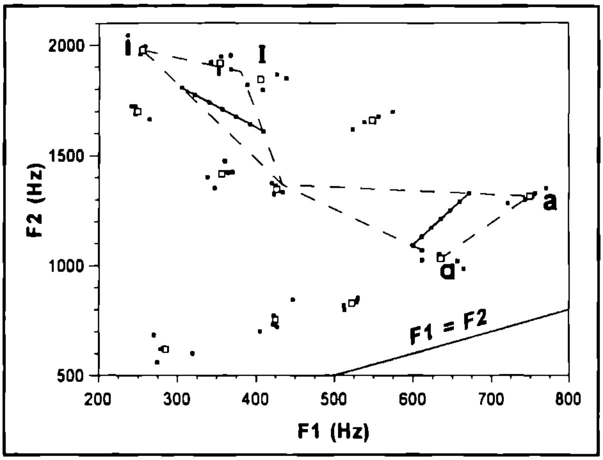
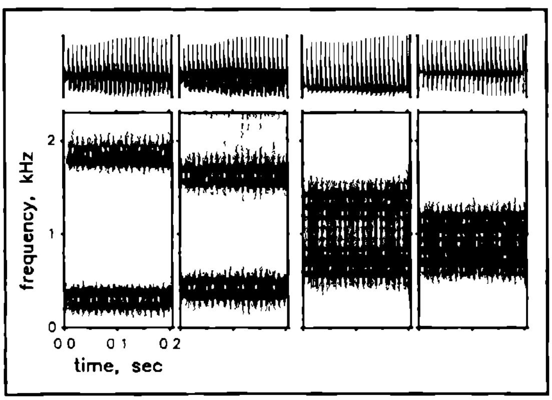



**TABLE 6.2.**
Frequencies (in Hz) for the first, second and third formant for the vowel stimuli of the two continua.

| | /i/-/I/ | | | /a/-/ɑ/ | | |
|---|---|---|---|---|---|---|
| Stim. | F1 | F2 | F3 | F1 | F2 | F3 |
| 1 | 305 | 1807 | 2805 | 671 | 1329 | 2502 |
| 2 | 322 | 1774 | 2761 | 680 | 1290 | 2496 |
| 3 | 340 | 1741 | 2716 | 689 | 1250 | 2489 |
| 4 | 357 | 1708 | 2672 | 698 | 1211 | 2483 |
| 5 | 374 | 1674 | 2627 | 707 | 1171 | 2477 |
| 6 | 392 | 1641 | 2583 | 716 | 1132 | 2470 |
| 7 | 409 | 1608 | 2538 | 725 | 1092 | 2464 |

*FIGURE 6 4*
*Waveforms and spectrograms of the endpoint tokens /i/, /I/, /a/ and /ɑ/*



### Procedure

The stimuli were recorded as in Experiment 1 and played back using a portable AIWA Digital Audio Tape recorder (Type AIWA HD S1 bit-stream D/A converter). Presentation was via a Beyerdynamic closed headphone (Type DT770). The playback level was set at the level judged as comfortable by the subject (always close to 70 dB HL). The subjects were tested in a quiet room at the school they were attending

Each child was examined in a one-hour session In order to accustom the child to the manipulated speech, he or she first heard five repetitions of the endpoint stimuli from the two continua withouth having to respond. After this, the subject was administered the identification and discrimination tasks. The two tasks (identification and discrimination) for the /i/-/I/ condition and the two tasks (identification and discrimination) for the /a/-/α/ condition were presented together, with the order counterbalanced across subjects Half of the subjects started with the /i/ /I/ condition, and half of the subjects started with the /a/-/α/ condition. Each condition started with the identification task followed by the discrimination task.

Each identification task consisted of a two-alternative forced choice response to a single auditory stimulus Ten repetitions of each of the seven stimuli of the continuum were presented in a random order consisting of five blocks of 14 stimuli each The stimuli were separated by interstimulus intervals of 3000 ms. For the /i/-/I/ condition, the subjects could identify the stimulus by pointing to one of two pictures: a picture of a man named Piet (/pit/), representing the stimulus /i/, and a picture of a pit (/pIt/), representing the stimulus /I/. For the /a/-/α/ condition, the subjects could identify the stimulus by pointing to one of two pictures a picture of a moon (/man/), representing the stimulus /a/, and a picture of a man (/mαn/), representing the stimulus /α/.

The AX discrimination task required a response of "same" or "different" on each trial. In order to obtain a bias-free measure of discriminability, the tasks were set up in such a way that signal detection measures could be applied (Coombs, Dawes & Tversky, 1970). For this, each task contained physically different as well as identical pairs There were two separate discrimination tasks, one for the /i/-/I/ and one for the /a/ /α/ continuum. In each task, the subjects heard two series of 21 discrimination pairs Each series contained two repetitions of the physically identical pairs 2 2, 3 3, 4-4, 5-5, 6-6, 7-7, and three repetitions of the physically different pairs consisting of stimulus 2, the so-called "anchor" stimulus for which the "just noticeable difference" (JND) was being measured; this resulted in pairs 2-3, 2-4, 2-5, 2-6 and 2-7. The "anchor" stimulus was always in first position in the pair. All pairs in one series were randomly ordered with an intrapair interval of 400 ms and an interpair interval of 3000 ms. The subjects were asked to point to a picture containing a triangle and a circle when the words in the pair they heard sounded different and simply not to respond when the words in the pair they heard sounded the same. The children were motivated by verbally reinforcing responses and nonresponses in a random fashion throughout the experiment Subjects never received differential feedback for particular responses

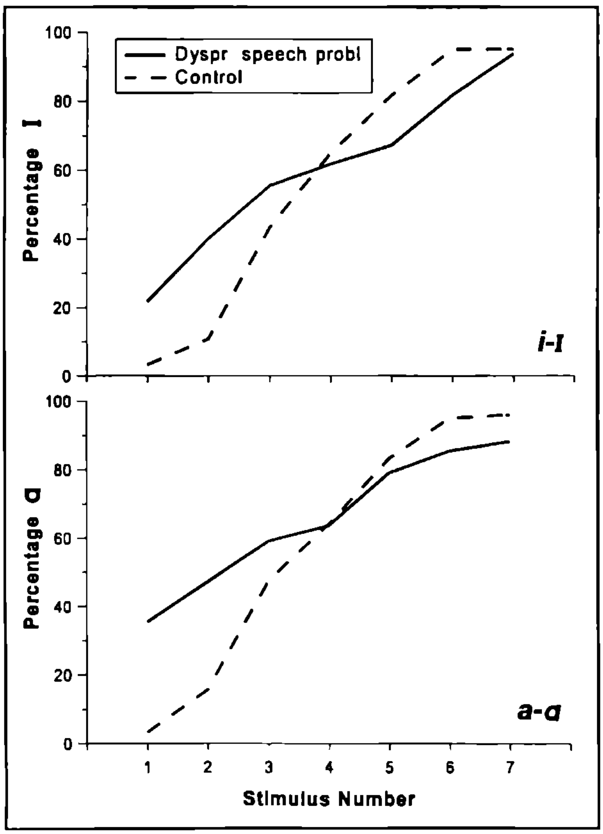
## Results

### *Identification*

In Figure 6 5, the mean identification curves for the groups in the /i/ /I/ and /a/ /α/ conditions are displayed Multivariate analyses of variance on the identification data (statistic Wilks' lambda) revealed a significant difference in identification patterns between the group of children with apraxic speech problems and the group of control children for the /i/ /I/ condition ($F$ [7,15]=3 12, $p$= 03) and the /a/ /α/ condition ($F$ [7,15]=4 93, $p$= 004)

In Figure 6 6 and Figure 6 7, individual identification curves are presented for the /i/ /I/ and the /a/ /α/ condition, respectively The articulation-disordered children were much more variable in their performance than the control children Common procedure when using speech continua is to evaluate and analyse speech perception data through probit analysis (e g , Groenen et al , 1996a, 1996b) The probit technique (Finney, 1971) yields slope and phoneme boundary values A high slope value indicates a small uncertainty range and suggests a highly consistent ability to categorize a speech contrast, whereas a low slope value indicates a large range and suggests difficulty in the identification of a speech contrast The probit technique assumes actual data to approach a cumulative normal distribution The data of the children with apraxic speech problems did not fit a cumulative normal distribution model (see e g , subject 7 in Figure 6 6, or subjects 3, 8, and 9 in Figure 6 7) The data of the control children, however, fitted a cumulative normal distribution model

*FIGURE 6 5*
*Mean percentages I (top) and 'α (bottom) responses as a function of stimulus number for the children with apraxic speech problems and control children*



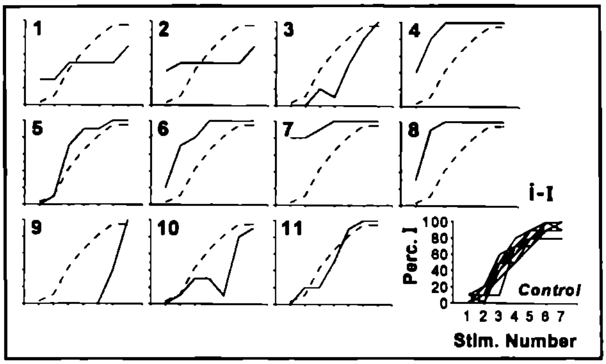



*FIGURE 6 6*
*Representation of individual identification curves for the /i/-/I/ condition Dashed lines represent the mean curve for the control children*

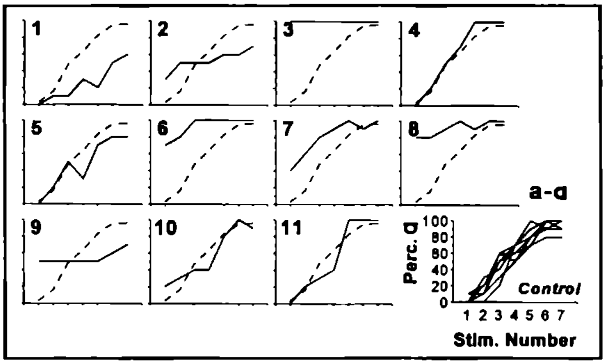



*FIGURE 6 7*
*Representation of individual identification curves for the /a/ /ɑ/ condition Dashed lines represent the mean curve for the control children*

To compare the identification results of both groups without having to estimate a cumulative normal distribution for each articulation-disordered subject, a measure of response variability was established For this, the mean probit curve of the control group was taken to predict prototypical identification values. For each subject, then, response variability was calculated by taking the sum of squared errors (actual percentage minus prototypical predicted percentage) across stimuli and dividing it by the total number of stimuli in the continuum. The resulting value was considered a penalty score of response variability. A low response variability value reflects close to normal identification performance, whereas a high response variability value reflects unstable or deviant identification performance.

**TABLE 6.3.**
Response variability in identification for the children with apraxic speech problems and control children

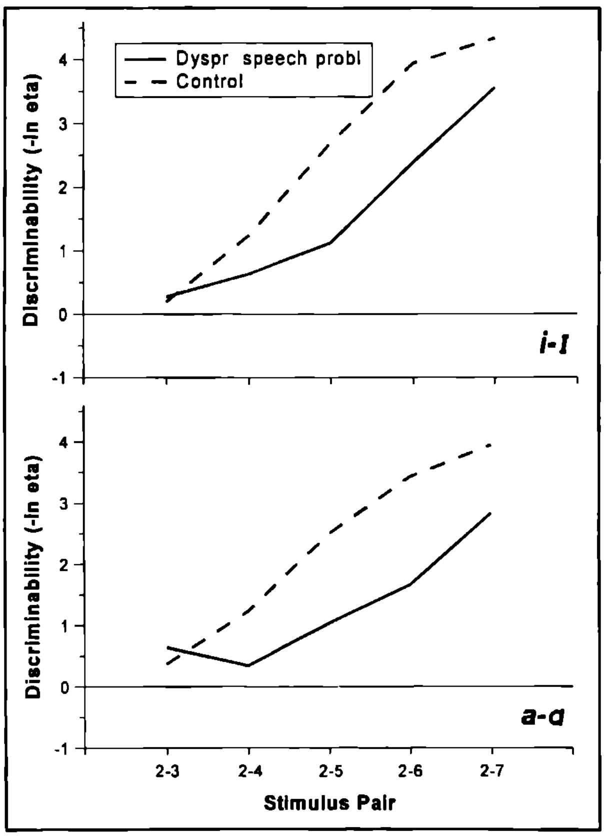
| | /i/-/I/ | | /a/-/ɑ/ | |
|---|---|---|---|---|
| | **M** | **SD** | **M** | **SD** |
| Aprax speech prob. | 1095 8 | 692 4 | 997 2 | 922.2 |
| Control | 79.6 | 42 5 | 80.6 | 50 1 |

In Table 6.3, for each condition, means and standard deviations of response variability are given for both groups *T*-tests were performed to test for differences in means between the groups. The *t* statistic was computed taking into account the equality or unequality of variances (see Freund and Littell, 1981). Under the assumption of unequal variances, the approximation of the degrees of freedom was computed using the formula of Satterthwaite (1946). There was a significant difference in response variability between both groups. Higher response variability values were found for the children with apraxic speech problems for both conditions (/i/-/I/, $t$ [10.1]=4.86, $p$<.001; /a/-/α/, $t$ [10.1]=3.29, $p$=.008). The articulation-disordered children showed a high amount of interindividual variation in response variability. For both conditions, the articulation-disordered group showed more variation in response variability than the control group (/i/-/I/, $F$ [10,11]=256.0, $p$<.001; /a/-/α/, $F$ [10,11]=339.08, $p$<.001).

### *Discrimination*

Discrimination results for each pair were expressed with the nonparametric estimate of d', yielding -ln eta scores (discriminability, Wood, 1976). The mean -ln eta results, as a function of stimulus pair, are shown in Figure 6.8 for the /i/-/I/ (top) and the /a/-/α/ (bottom) condition, respectively. Discriminability (-ln eta) equals zero when performance is at chance. It increases with greater accuracy of discrimination, without influences of bias to respond "same" or "different". Discriminability is maximal at the value of -ln eta of 4.6. This 4.6 value is obtained when the probabilities of correct "different" and correct "same" responses are both .99, which was the value assigned (for computational purposes) when the obtained proportions were 1.00

*FIGURE 6.8*
*Mean discrimination scores as a function of stimulus pair for the children with apraxic speech problems and control children for the /i/-/I/ (top) and the /a/-/α/ (bottom) condition*



A 2-way ANOVA (Group x Stimulus Pair) with repeated measures on Stimulus Pair was performed. Significant differences between the children with apraxic speech problems and control children were found for both conditions. There were significant effects of Stimulus Pair, indicating that the children in both groups showed increasing discriminability values with increasing physical stimulus difference (/i/-/I/, $F[4,84]=65.81$, $p<.001$; /a/-/ɑ/, $F[4,84]=47.64$, $p<.001$). There were significant effects of Group, indicating that the overall discrimination level of the articulation-disordered children was lower than that of control children (/i/-/I/, $F[1,21]=8.42$, $p=.009$; /a/-/ɑ/, $F[1,21]=7.26$, $p=.01$). In addition, there was a significant Group x Stimulus Pair interaction for both conditions (/i/-/I/, $F[4,84]=3.43$, $p=.01$; /a/-/ɑ/, $F[4,84]=5.05$, $p=.001$). This indicates a dissimilar pattern of responses for the two groups and may reflect differences in slope of the discrimination curve.

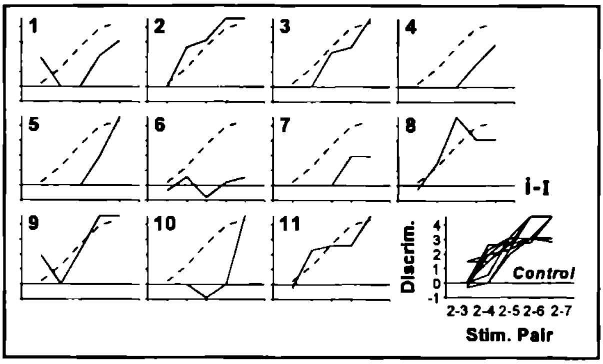



*FIGURE 6 9*
*Representation of individual discrimination curves for the /i/ /I/ condition Dashed lines represent the mean curve for the control children*

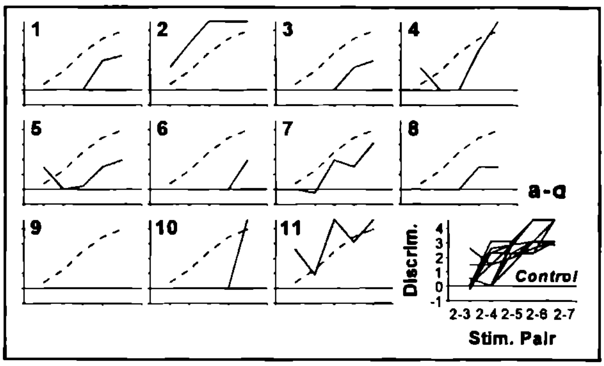



*FIGURE 6 10*
*Representation of individual discrimination curves for the /a/ /ɑ/ condition Dashed lines represent the mean curve for the control children*

In Figures 6.9 and 6.10, individual discrimination curves are presented for the /i/-/I/ and the /a/-/ɑ/ condition, respectively. The articulation-disordered children demonstrated much more variability in their discrimination performance than the control children. For both conditions, the articulation-disordered group seemed to demonstrate shallower discrimination functions than the control group. To substantiate this, for each subject JND measures of sensitivity were computed. Linear regression analyses were performed on the individual discrimination functions. JNDs could be determined by computing the interpair difference that provided a discriminability of 50% of the maximum discriminability value (i e., -ln eta = 2.3). If computed JNDs exceeded a value of 6, for statistical purposes, a value of 6 (the maximum physical difference between stimuli in a pair (2-7) plus 1) was assigned.

In Table 6.4, JND results are presented for the children with apraxic speech problems and the control children *T*-tests were performed to test for differences between the groups. There were significant differences in JND between both groups Higher JNDs were found for the children with apraxic speech problems for both conditions (/i/-/I/, $t\,[11.9]=2.85$, $p=.01$; /a/-/α/, $t\,[12.2]=2.82$, $p=.01$). Children with apraxic speech problems required a greater acoustic difference between two stimuli in order to differentiate between them than control children. In addition, the articulation-disordered group showed a higher amount of interindividual variation in JND values than the control group (/i/-/I/, $F\,[10,11]=9.59$, $p<.001$, /a/-/α/, $F\,[10,11]=8.28$, $p=.001$)

**TABLE 6.4.**
JND results for discrimination for the children with apraxic speech problems and control children

| | /i/-/I/ | | /a/-/α/ | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Aprax speech prob | 4 01 | 1 32 | 4.66 | 1.83 |
| Control | 2.83 | 0.42 | 3.02 | 0.63 |

Note.
JND = Just Noticeable Difference

## *Classification of Patterns*

In Figures 6.6, 6.7, 6.9, and 6.10, individual identification and discrimination curves were presented. The articulation-disordered children seemed much more variable in their performance than the control children. Children with an articulation disorder may be categorized into subgroups according to their speech perception performance. Instead of subjectively dividing the group of articulation-disordered children into subgroups by eye, an objective measure was established. Methods of randomization testing (Edgington, 1987) were used to single out - in a nonparametrical fashion - from the children with articulation problems a subgroup showing similar atypical perception patterns. Exhaustive randomization testing (see Groenen et al., 1996b for a detailed description) was performed and all possible solutions for the selection of one subgroup of five and another subgroup of six children were evaluated. Objective determination of an optimal solution of a subgroup showing coherent atypical perception patterns was based on a test statistic which was equivalent to *F* for MANOVA. Increasing *F*s reflect increasing differences between groups To make an exhaustive search for the best division, all possible solutions for selecting a subgroup of five out of 11 children (462 permutations) were tested. The division associated with the highest test statistic reflected optimal subgrouping. For identification, the labelling scores for each stimulus, and for discrimination, the scores for each stimulus pair were used to compute optimal subgrouping.

Optimal subgrouping of identification patterns for the /i/-/I/ condition occurred with subjects 4, 5, 6, 7, and 8 ($p=.002$, i e. 1/462, by randomization test). Visual inspection of the identification data of these subjects, yielded a general atypical perception pattern with a bias toward making /I/ responses The remaining six subjects showed normal patterns of perception (subject 11), a bias toward making /i/ responses (subjects 3, 9, and 10), and high inconsistency levels (subjects 1 and 2) For the /a/ /ɑ/ condition, the identification patterns of subjects 3, 4, 6, 7, and 8 formed the optimal subgroup (*p*= 002, by randomization test) with subject 4 showing close to normal identification The character of atypical similarity for the five subjects in this subgroup concerned a strong bias toward making /ɑ/ responses. The remaining six subjects showed normal patterns of perception (subjects 10 and 11), a bias toward making /a/ responses (subjects 1 and 5), and high inconsistency levels (subjects 2 and 9).

Optimal subgrouping of discrimination patterns for the /i/-/I/ condition occurred with subjects 1, 4, 5, 6, 7, and 10 (*p*= 002, by randomization test) These subjects demonstrated atypical discrimination patterns characterized by a shallow discrimination curve (i.e., large JND values). The remaining five subjects showed patterns of discrimination which were similar to those of the control children For the /a/-/ɑ/ condition, clustering the discrimination patterns of subjects 1, 3, 6, 8, 9 and 10 resulted in the optimal subgroup (*p*= 002, by randomization test) The sub-



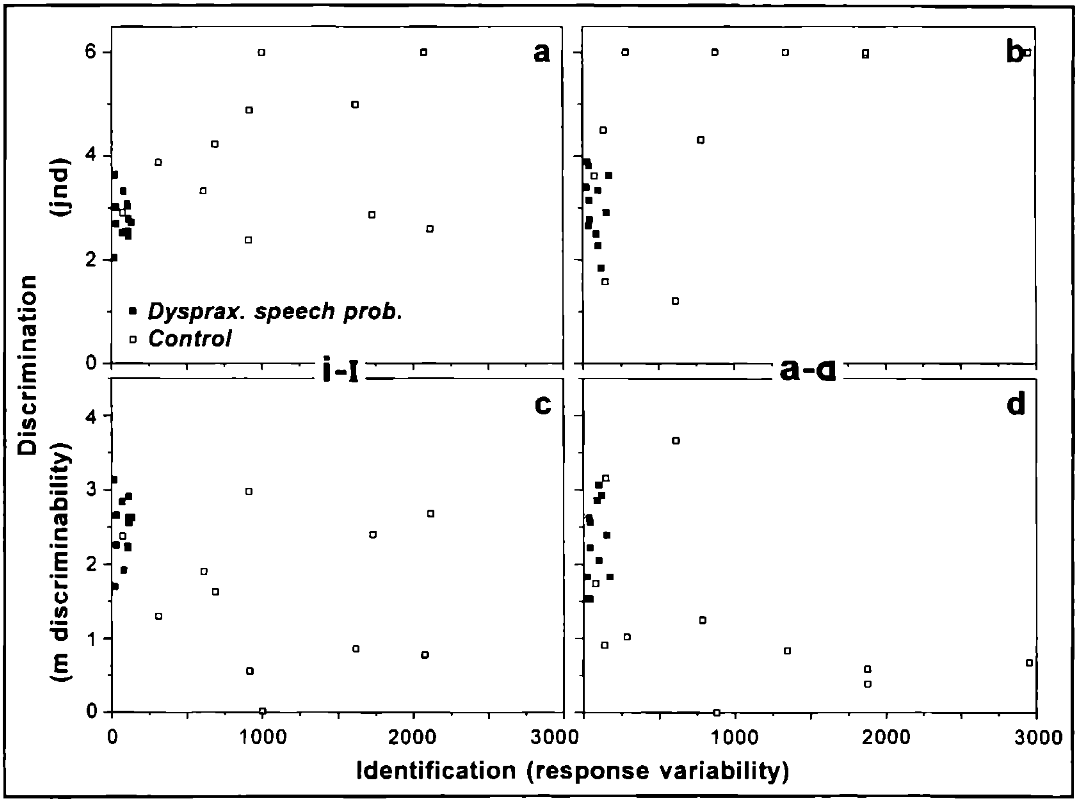



*FIGURE 6 11*

*Scatterplot of the individual identification and discrimination scores (a) response variability versus JND for the /i/ /I/ condition, (b) response variability versus JND for the /a/ /ɑ/ condition, (c) response variability versus mean discriminability for the /i/ /I/ condition, and (d) response variability versus mean discriminability for the /a/ /ɑ/ condition* jects of this subgroup showed atypical shallow discrimination patterns (large JND values). The remaining five subjects showed a variable pattern of discrimination.

### *Clinical value of perceptual measures*

In Figure 6 11, scatterplots are presented of individual results of identification ver sus discrimination. One measure of identification (response variability) and two measures of discrimination (average discriminability across stimulus pairs, and JND) were taken into consideration. There was a high degree of clustering in the group of control children whereas the articulation-disordered children were very variable in their performance. To substantiate the apparent clinical value of perceptual measures, randomization testing was used on the total group of subjects (including both articulation-disordered and control children, i.e., N=23) to single out the poorest performing cases based on a combination of their identification and discrimination performance. Exhaustive randomization testing was performed on a combination of response variability for identification and JND for the /i/-/I/ and the /a/-/α/ condition (see data in Figures 6.11a and 6 11b, respectively), and response variability and mean discriminability for the /i/-/I/ and the /a/-/α/ condition (see data in Figures 6.11c and 6.11d, respectively) All possible solutions for the selection of a subgroup of three to 11 poorest performing children were tested (the test statistic used was equivalent to *F* for MANOVA). The result was a set of subgroups ranging from 3 to eleven. The subjects in each subgroup showed coherence and differed maximally from the rest of the group.

**TABLE 6.5.**
Clinical value of perception measures.

| | /i/-/I/ | | | | /a/-/α/ | | | |
|---|---|---|---|---|---|---|---|---|
| Total | RV/JND | | RV/Discr. | | RV/JND | | RV/Discr | |
| N=23 | n | % | n | % | n | % | n | % |
| subgroup (n) | | | | | | | | |
| 11 | 10 | 91 | 9 | 82 | 9 | 82 | 9 | 82 |
| 10 | 10 | 100 | 9 | 90 | 9 | 90 | 9 | 90 |
| 9 | 9 | 100 | 9 | 100 | 8 | 89 | 8 | 89 |
| 8 | 8 | 100 | 8 | 100 | 8 | 100 | 8 | 100 |
| 7 | 7 | 100 | 7 | 100 | 7 | 100 | 7 | 100 |
| 6 | 6 | 100 | 6 | 100 | 6 | 100 | 6 | 100 |
| 5 | 5 | 100 | 5 | 100 | 5 | 100 | 5 | 100 |
| 4 | 4 | 100 | 4 | 100 | 4 | 100 | 4 | 100 |
| 3 | 3 | 100 | 3 | 100 | 3 | 100 | 3 | 100 |

**Note.**
RV = Response Variability (identification); JND = Just Noticeable Difference (discrimination); Discr. = Mean Discriminability (discrimination). For example, when taking a combination of measures of response variability and JND to establish an optimal objective division (using a criterion of the highest F statistic from multiple randomization tests) of the total group of subjects (including all children with apraxic speech problems and all control children, i e , N=23) consisting of subgroups of 11 and 12 subjects, for the /i/-/I/ condition, 10 out of the 11 (i e , 91%) subjects in one subgroup are children with apraxic speech problems.

For each subgroup, the number of children with apraxic speech problems was counted. This result converted to percentage was considered an expression of the clinical value. In Table 6.5, the number of articulation-disordered children in each subgroup is presented. For example, when taking a combination of measures of response variability and JND to establish an optimal objective division of the total group consisting of subgroups of 11 and 12 subjects (1 out of 1,352,078 possibilities), for the /ı/-/I/ condition, 10 out of the 11 (i.e , a clinical value of 91%) subjects in one subgroup were children with apraxic speech problems.

For subgroups up to eight subjects, the clinical value was 100% for all conditions and for every combination of identification and discrimination measures; from the eight poorest performing subjects in perception, eight subjects had apraxic speech problems. The clinical value slightly decreased with subgroups greater than eight subjects but never went below 82%. This suggests that (a) most of the articulation-disordered children showed perceptual problems, and (b) a combination of perception measures (identification and discrimination) to have a high differential value for the assessment of children with apraxic speech problems.



## General Discussion

The main conclusions from this study were:

1) The group of children with apraxic speech problems demonstrated poorer perception of vowels than the control children for both the /ı/-/I/ and the /a/ /a/ continuum. This was found on two levels:
   (a) They demonstrated a shallower mean identification function and a higher mean response variability for both the /ı/-/I/ and the /a/-/α/ condition than the control children, indicating poorer phonetic processing
   (b) The overall discrimination level of the articulation-disordered children was lower than that of control children for both vowel conditions. In addition, higher JNDs were found for the children with apraxic speech problems for both conditions. Children with apraxic speech problems showed a need for acoustic speech redundancy and required a greater auditory difference between two stimuli in order to differentiate between them than control children The children with apraxic speech problems demonstrated poorer discrimination than the control children, which indicates poorer auditory processing.
2) The children with apraxic speech problems showed a high amount of interindividual variation in both identification and discrimination. For identification, apart from subjects with perception patterns similar or close to the pattern of control children, subgroups with coherent atypical perception patterns were characterized by (a) a bias towards one specific response, (b) inconsistent labelling (i.e., shallow identification curve). For discrimination, subgroups with coherent atypical perception patterns were characterized by a shallow slope (i e., large JND values).
3) A combination of perception measures (identification and discrimination) proved to have a high differential and clinical value for the assessment of children with apraxic speech problems

Our finding of a relation between perception of vowels and articulatory function adds to the established relation between consonant perception and articulatory deficits in diverse groups of subjects (Broen, Strange, Doyle, & Heller, 1983; Groenen et al , 1996b; Hoffman, Daniloff, Bengoa, & Schuckers, 1985; Hoit-Dalgaard, Murry, & Kopp, 1983, Monnin & Huntington, 1974; Ohde & Sharf, 1988; Raaymakers & Crul, 1988; Rvachew & Jamieson, 1989).

In Groenen et al. (1996b, 1994), consonant perception was studied in a group of children with developmental apraxia of speech and developmental dyslexia. Their results posed some problems about the relation between auditory and phonetic processing. Hierarchical dual-coding models of speech perception did not provide a clear rationale for finding auditory processing to be disturbed and phonetic processing to be intact The results supported a structure for speech processing with an auditory stage and a phonetic stage partly allowing for stage-independent output and the integrity of phonetic processing not being totally dependent on the outcome of auditory processing: a structure similar to the one posed by Ades (1977), suggesting the possibility of phonetic processing not receiving input from acoustical traces and instead forming an entirely independent route In the present study, we used vowels and found that children with apraxic speech problems showed atypical perception on both an auditory and phonetic level. Part of the difficulties encountered by Groenen et al. (1996b) were eliminated by using vowels instead of consonants Vowels seemed to more sensitively assess the auditory/phonetic distinction than consonants. The inherent lower identifiability of vowels (and consequently, more pronounced representation in auditory memory) facilitated a reliable, straightforward interpretation of findings about the auditory and phonetic nature

Central auditory processing disorders of speech sounds tend to manifest themselves in perceptually aggravated conditions. In Groenen et al (1996b), synthetic and resynthetic speech was used to assess speech perception in articulation-disordered children. In the synthetic condition, the redundancy of speech material was reduced by focussing on overall spectral poorness (the intensity of the third formant). This manipulation did not have any differential value and did not make the perception test more sensitive In Groenen et al (1996a), long-term effects of otitis media with effusion on speech perception in a group of children were studied and compared to control groups. Speech-in-noise tasks, and identification and discrimination tasks based on speech continua were administered. Speech-in-noise tasks typically aim at assessing central auditory processing (see Katz, 1994). Speech-in-noise recognition abilities were the same for both groups whereas the groups differed in identification and discrimination performance. It was suggested that degradation of the stimuli with non-linguistic information (e.g., adding noise, reducing spectral richness) simply did not tap into speech perception problems because of the potentially marginal relation to the speech signal and the specific processes of speech perception. The manipulations lacked psycholinguistic relevance

Instead of reducing the redundancy of the speech signal without reference to psycholinguistic dimensions, in the present study the redundancy of the vowel stimuli was reduced by decreasing vowel contrast and partly neutralizing the spectrum in an ecologically valid way (see Experiment 1). Moving the vowel formants to the speaker-centroid (i e., "neutral-vowel position") can be considered a type of reduction of the redundancy of the speech signal directly concerning entities that have ecological and psycholinguistic value. Speaker centroids seem anatomically determined and representative of the vocal tracts and vowel contrast reduction towards the speaker-centroid reflects different speaking conditions (Koopmans-van Beinum, 1980). The results with this type of reduction confirmed suggestions made in Groenen et al. (1996a, 1996b) about reductions of the redundancy based on dimensions with psycholinguistic relevance to easier tap into central auditory processing problems of speech sounds than reductions of the redundancy of the speech signal based on dimensions without psycholinguistic relevance.

Perception and production processes are likely to interact during language acquisition and development (Liberman, 1996). There seems to be no straightforward causal relation between perception and production. On the one hand, there are signs that production can affect perception (e.g., Monnin & Huntington, 1974) Hoffman et al. (1985) hypothesized that productive neutralization may lead to perceptual ignorance. On the other hand, contrary to the idea that production precedes perception, an explanation of perception preceding production is viable. Studies of normal perception and production skills have shown many instances of perception preceding production In reviewing the potential causal relation between perception and production, Strange and Broen (1980) point out that human infants appear to be sensitive to acoustic-phonetic dimensions that allow them to perceive phoneme contrasts far in advance of any ability to produce such contrasts Broen et al. (1983) found that children identified as articulatory-delayed showed less discre te categorization of /r/ and /w/ than children with normal articulatory development. Both groups of children, however, misarticulated /r/ as /w/. This finding suggested that normally developing children had developed perceptual ability ahead of production ability. Kuhl (1991) showed that vowel prototypes exist at an age of six months, serving as language-specific "perceptual magnets" for other stimuli Contemporary models of speech perception such as the Native Language Magnet (NL) theory (Kuhl, 1993) and the Word Recognition and Phonetic Structure Acquisition (WRAPSA) model (Jusczyk, 1993) suggest that during the first year of life, prior to the time that infants acquire word meaning and contrastive phonology and prior to the critical time for the development of production skills, essential phonetic perception strategies have been developed. We, therefore, favor an interpretation of perception skills preceding production skills.

As we referred to in the introduction, more specific data on the development of auditory perceptual skills of children with apraxic speech problems are scarce (Hall et al., 1993). According to Locke (1994) " ..neuromaturational delay is responsible for many of the children's auditory, visual, and tactual perceptual deficits. These performance deficits will look like the causes of whatever is running late at the moment, but they are indices of a brain whose development is behind schedule." Pollock and Hall (1991) mention the problem of what factors underly vowel misarticulations in children with apraxic speech problems. Do children who misarticulate vowels have difficulty forming stable target representations, or is the problem related to inadequate motor control? Our study provided evidence that not only vowel production but also vowel perception is affected This suggests misarticulation of vowels in children with apraxic speech problems to be a difficulty related to target representations of vowels. The internal representations of vowels seem to be poor which, in turn, affects both production and perception.

The present study shows that auditory perception of vowels in children with apraxic speech problems is affected They demonstrate poorer auditory and phonetic processing. The articulation-disordered children exhibit a high amount of inter-individual variation in both identification and discrimination. A combination of perception measures (identification and discrimination) proves to have a high differential and clinical value for the assessment of children with apraxic speech problems. These facts must be considered in the diagnosis of apraxic speech disorders and in the development of therapy.



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Chapter 7

# THE RELATION BETWEEN COGNITIVE TONE AND SPEECH-EVOKED P300 POTENTIALS AND SPEECH PERCEPTION ABILITY IN COCHLEAR IMPLANT USERS

*Paul Groenen, Ad Snik, Paul van den Broek*

## Abstract

Processing in the auditory cortex may play a role in the unexplained variability in cochlear implant benefit P300 and N1/P2 were elicited in postlingually deaf cochlear implant users wearing a Nucleus multichannel cochlear implant. Four sound contrasts were presented (pure tones, and speech sounds). P300 results of the cochlear implant users were compared to behavioral results of speech perception ability Prolonged N1, P2 and P300 latencies were found in the cochlear implant group. The amplitude of N1 was smaller for the speech signals The amplitude of P2 was smaller for the consonants There was a relation between P300 quality and behavioral speech perception in cochlear implant users The poorer cochlear implant performers demonstrated smaller P300 amplitudes and magnitudes than the better performers The results suggest that P300 measurements are useful in evaluating and monitoring the neural functionality and may help in developing rehabilitation programs for cochlear implant users

## Introduction

One challenge in cochlear implant research is to explain the variability in the subjects' results with a cochlear implant Processing in the auditory cortex may play a role in the unexplained variability in cochlear implant benefit A major question, then, is whether and how objective measures of neural integrity are related to subjective performance For a reliable understanding of the effects of electrical stimulation of the inner ear, this crossvalidation is very important. Hypothesizing that the "bottleneck of success" of electrical cochlear stimulation is the integrity of successive multiple neural centres, electrophysiological assessment could well be a differential indicator of current or even future attainable subjective performance

The P300 is elicited in an "oddball paradigm", in which an unexpected stimulus occurs in a series of expected stimuli. It is an objective measure of the discrimination of stimulus differences. Processes of attention, auditory discrimination, memory and semantic expectancy appear to be involved in the generation of P300. The P300 is thought to represent a general cognitive response that originates from multiple auditory and nonauditory structures. It is suggested that the frontal cortex, centroparietal cortex, and the auditory cortex contribute to the P300 (see Kraus & McGee[1]). Measuring event related potentials seems especially useful when testing subjects with problems of speech processing It has been demonstrated that speech perception problems rarely are of general nature, but concern specific speech features.[2,3,4] Therefore, to get a valid neurophysiological profile of speech processing, one has to present several sound contrasts. For clinical practice, especially in cases where an immediate diagnosis cannot be made, it is desirable to gather a maximum amount of information. The P300 is a large response, requiring averaging of only 20-30 presentations of target stimuli [1] Therefore, the P300 involves a technique that allows for presenting different sound contrasts in a relatively short time.

The P300 has been evaluated in subjects with a wide range of disorders, e.g , Parkinson's disease, chronic renal failure, chronic alcoholism, dementia, cerebrovascular lesions, head trauma, brain tumors, schizophrenia, and aphasia.[1] There is an increasing amount of literature on event-related potentials elicited in subjects with a cochlear implant. Event-related P300 measurements using tone bursts in subjects with a cochlear implant were performed in several studies.[5,6,7,8] In all studies, significant P300 peaks were found. P300 measurements using speech in successful cochlear implant users were performed by Micco et al.[9] They found no significant differences in P300 amplitude and latency between the group of cochlear implant users and a group of age-matched subjects with normal hearing

It is commonly recognized that objective measurements of event-related potentials can provide a neurophysiologic basis for the evaluation and the development of rehabilitation programs for cochlear implant subjects.[10,11] Most of the studies using objective measurements in subjects with a cochlear implant have focused on highly successful implant users In our opinion, this typically is not the group that can benefit most from neurophysiologic objective measurements Moderate and poor performers are likely to benefit more from highly developed rehabilitation programs than good performers. There is a need for knowledge on neurophysiologic processes in less successful cochlear implant users

Most of the studies so far did not compare electrophysiologic results to behavioral results of speech perception. Therefore, not much is known about the relation between the quality of auditory evoked potentials and speech perception performance In a few case studies it was found that in a poor CI user electrophysiologic indices of stimulus discrimination were absent.[12,9] Groenen, Makhdoum, et al [8] found that good cochlear implant performers showed normal P300 latencies, whereas in moderate performers, the P300 latencies were prolonged Although these results are not exclusive, they suggest that electrophysiological indices of stimulus discrimination are related to cochlear implant benefit

In the present experiment, P300s were elicited by tone and speech stimuli in a group of postlingually deaf cochlear implant users. The tone contrast consisted of a 500 Hz and a 1000 Hz tone burst. A consonant place-of-articulation contrast /bα/-/dα/ was constructed, in which the target cue for auditory discrimination solely was the spectral transient of the second and third formant, the vowel characteristics where kept alike. Then, a consonant voicing contrast /bα/-/pα/ was used, in which the target cue for auditory discrimination was of temporal nature. Finally, a vocalic contrast /i/-/a/ was used, which was characterized by a speechlike difference in timbre In addition to P300 responses, stimulus detection components N1 and P2 were examined and compared P300 results of the cochlear implant users were compared to behavioral results of their speech perception ability

Summarizing, the present study extends previous research in several ways by: (a) presenting both tone and speech sound contrasts (consonants and vowels), and (b) comparing the objective measurements to behavioral measures of speech perception ability

## Method

### *Subjects*

Subjects were nine adult post-lingually deaf subjects with a Nucleus multichannel cochlear implant and an MSP processor. Audiological measurements prior to implantation showed total deafness in all cases, which meant that the hearing thresholds at 500 Hz exceeded 110 dB HL and at 1000, 2000, 4000 and 8000 Hz they exceeded 120 dB HL Some subject data are presented in Table 7.1 In all the subjects, the electrode array was inserted into the cochlea over its full length All the subjects were using a bipolar+1 (BP+1) MAP with the MPEAK speech processing strategy. The subjects were experienced users of the cochlear implant; they had been using it all day for several years. The integrity of the implant was checked according to Mens, Oostendorp, and Van den Broek[13]; the amplitudes of the biphasic pulses were within the normal range and showed no discontinuities. Similarly, the behavioral threshold and comfort levels (C-levels) of all the subjects did not show any conspicuous discontinuities. Electrical middle-latency response measurements showed good reproducible traces in all nine subjects

The control subjects were 10 adults (5 females, 5 males, mean age 28;0 years, range 24;06 to 57,1 years) They had no history of hearing, speech or language, or neurological problems. They had hearing thresholds (at 250, 500, 1000, 2000, 4000 Hz) below 15 dB HL for either ear

TABLE 7.1.
Subject characteristics.

| Pat. | Age at onset (Yrs) | Duration | Etiology (Yrs)1 | Perception score (%)2 |
|---|---|---|---|---|
| S1 | 12 | 5 | unknown | 78 |
| S2 | 61 | 2 | trauma | 65 |
| S3 | 6 | 22 | unknown | 90 |
| S4 | 7 | 44 | meningitis | 52 |
| S5 | 49 | 2 | unknown | 100 |
| S6 | 15 | 3 | meningitis | 60 |
| S7 | 26 | 6 | hereditary | 63 |
| S8 | 60 | 8 | hereditary | 60 |
| S9 | 26 | 36 | unknown | 91 |

Note.
[1] Duration of deafness is the difference in years between the onset of deafness and cochlear implantation [2] A composite score for speech perception was obtained, which was the average score for a monosyllable identification test, a spondee identification test, a long-vowel recognition test, and a short-vowel recognition test (see Behavioral testing under Methods)

### *Stimuli*

Both tone and speech sound contrasts were used. Auditory late (N1/P2) and cognitive (P300) responses were elicited with sound contrasts utilizing an oddball paradigm.

*Tone contrast*

A 500 Hz tone burst (20 ms linear rise and fall time, 80 ms plateau time) was used as the standard stimulus, whereas a 1000 Hz tone burst (with the same envelop) was used as a deviant stimulus. These stimuli were generated by the Interactive Laboratory System V6.1.

*Speech contrasts*

Three speech sound contrasts were constructed. The Computerized Speech Lab (CSL Model 4300, V5.05) was used for editing sound signals. The LPC Parameter Manipulation/Synthesis Program (ASL Model 4304, V1) was used for manipulating and resynthesizing the spectral structure of the signal. Firstly, a place-of-articulation contrast /bα/-/dα/ was constructed, which was a contrast determined by spectral cues. A natural adult male voice formed the base of the speech tokens. By manipulation of the linear predictive coding (LPC) parameters and resynthesis of the result, the two words were constructed. A pitch asynchronous autocorrelation method (pre-emphasis factor: .95, Hamming window, frame length: 150 points, filter order: 12) was used, see Markel & Gray[14] for details on LPC.

The two speech tokens differed from one another in the starting value and slope of the transitions of the second and third formant. For /bα/, F2 and F3 started at 1000 and 2150 Hz, respectively. For /dα/, F2 and F3 started at 1500 and

3150 Hz, respectively. F1 started at 400 Hz. The transition of the first formant was 30 ms in duration. The transitions of the second and third formants were 45 ms in duration All transitions were linear The final 64 ms of the vowel consisted of steady-state formants appropriate for the Dutch vowel /α/ with center frequencies at 750 Hz (F1), 1150 Hz (F2), and 2500 Hz (F3). The sampled data were resynthesized with a pitch-asynchronous synthesis procedure The total length of each stimulus was 175 ms

Secondly, a voicing contrast /bα/-/pα/ was constructed. This contrast is determined by temporal cues The major acoustic cue carrying voicing information in Dutch is voice onset time (VOT).[15] In comparison to the English voicing distinction, the Dutch voicing distinction is differently distributed along the VOT dimension. Whereas the English values fall into a range between 0 and +100 ms, Dutch stop category values fall into a range between -100 and +10 ms.[16] The speech token /bα/ of the place of-articulation contrast was taken for constructing the voicing contrast. The initial consonant of the /bα/ token was given a 46 ms voice lead. To create a voice lagged /pα/, the voice lead was removed and a 12 ms silent interval was inserted after the burst of the initial consonant. The total duration of /bα/ was 163 ms, the total duration of /pα/ was 129 ms

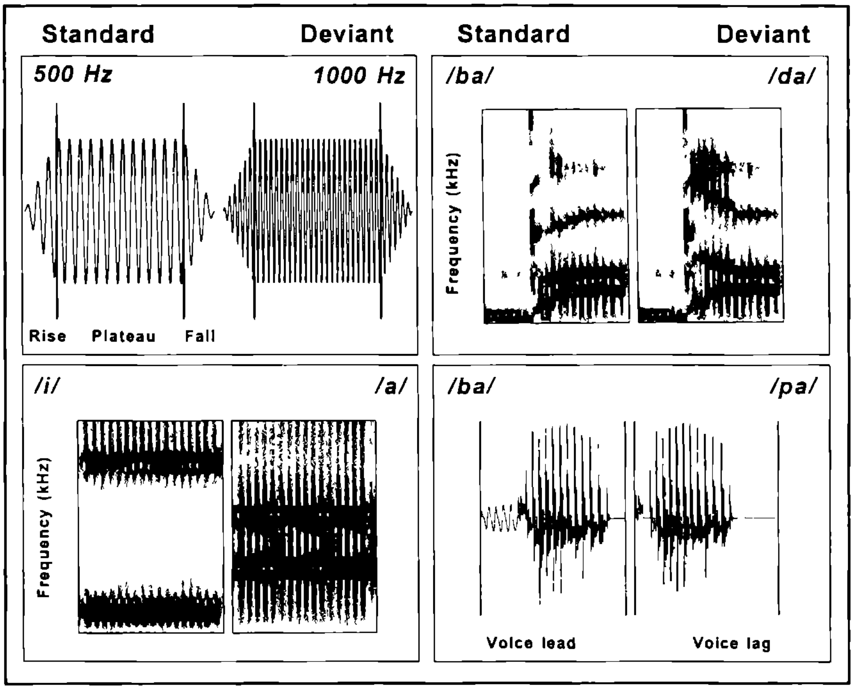


*FIGURE 7 1*

*Oscillograms and spectrograms displaying the sound contrasts The wave forms of the tone stimuli do not reflect the actual frequency and merely function to visualize the envelop and the difference in frequency between 500 and 100 Hz*

Thirdly, a vowel contrast /i/-/a/ was generated This contrast was determined by formant frequencies of the first, second, and to a lesser extent the third formant A natural adult male voice formed the base of the speech token /i/ A similar procedure to that in generating the place-of-articulation contrast was followed. The spectral structure of the steady-state formant frequencies was manipulated. The two speech tokens differed from one another in the center frequencies of the first, second and third formant. For /i/, F1, F2 and F3 was set to 255, 1980, and 2950 Hz, respectively For /a/, F1, F2 and F3 was set to 750, 1315, and 2525 Hz, respectively The total length of each stimulus was 150 ms.

Stimulus phonemic quality was checked by having 10 adults label 10 repetitions of each of the speech sound stimuli presented in random order The percentages correct identifications were above 97% for all words Stimulus phonemic quality was also checked in a group of five successful cochlear implant users The percentages correct identifications were above 72% for all words. The identification results warranted phonetic processing of the stimuli and indicated a valid choice of spectral and temporal manipulations.

In Figure 7.1, oscillograms and spectrograms displaying the sound contrasts are presented.

### *Procedure*

The stimuli were acoustically presented by a loudspeaker placed 1 m in front of the subject. The standard stimuli occurred at a probability rate of 85%; the deviant stimuli occurred at a probability rate of 15%. The presentation level at the position of the subjects' ears or cochlear implant microphone was approximately 70 dB(A) (measured with Bruel and Kjaer 2203 soundlevel meter). Recording electrodes were placed on the right mastoid (M2, reference) for the subjects with normal hearing and on the contralateral mastoid (Mc, refererence) for the cochlear implant users, on the forehead midline (Fz, active) and on the wrist (ground) A computer was used for stimulus presentation and to trigger an evoked potential registration system (Medelec ER94). The system was set for a 1000 ms analysis time with the EEG filtered from 1 to 125 Hz. Eye movements were detected and contamination by eye movements was checked Measurements showing artefacts caused by eye movements were excluded from the average. The recordings of two standard stimuli following a deviant stimulus were not included in the average Afterwards, the recordings were zero phase-shift low-pass filtered digitally off-line, with a cut-off frequency of 25 Hz. The inter-stimulus interval was set at 2s.

The subjects were tested in one session. For each sound contrast, evoked potentials were measured from 2 blocks of the stimuli. Each block comprized presentation of 20 standard stimuli, followed by 30 deviant stimuli pseudorandomly embedded in about 170 standard stimuli Between two deviant stimuli at least three standard stimuli were presented. The subjects had their eyes closed during recording and were instructed to count the deviant stimuli.

All subjects started with the tone contrast condition followed by the three speech sound conditions The order in which the speech sound conditions were presented was varied across subjects

### Data analysis

For each subject, individual subaverages of the blocks were computed The P300 is, by definition, elicited only by the deviant stimulus Therefore, difference waves were computed for each block by subtracting the averaged response to the deviant stimuli from the averaged response to the standard stimuli. The P300 was identified visually as a positivity in the 200 800 ms region

Several measures of P300 integrity were established: (1) peak latency, the latency at maximum negativity of the P300 response; (2) amplitude at peak latency; (3) P300 magnitude (the area under the P300) determined by P300 duration times P300 amplitude (P300 duration was measured as the time between consecutive zero-crossings) In addition to individual determination of P300 quality, overall measures of P300 quality were computed on the grand average across all subjects Measures of P300 quality were derived from the difference wave

### Behavioral testing

Several perception tests were administered to cochlear implant users Follow up data up to 2 years post implantation were collected as part of the evaluation procedure in the Nijmegen Cochlear Implant programme. Performance at 1 year post-implantation had reached a ceiling effect.[17] Performance at this moment was used as a reference Perception was assessed by means of the Antwerp-Nijmegen (AN) test battery [18,19] The AN test had a setup similar to that of the MAC and Iowa test



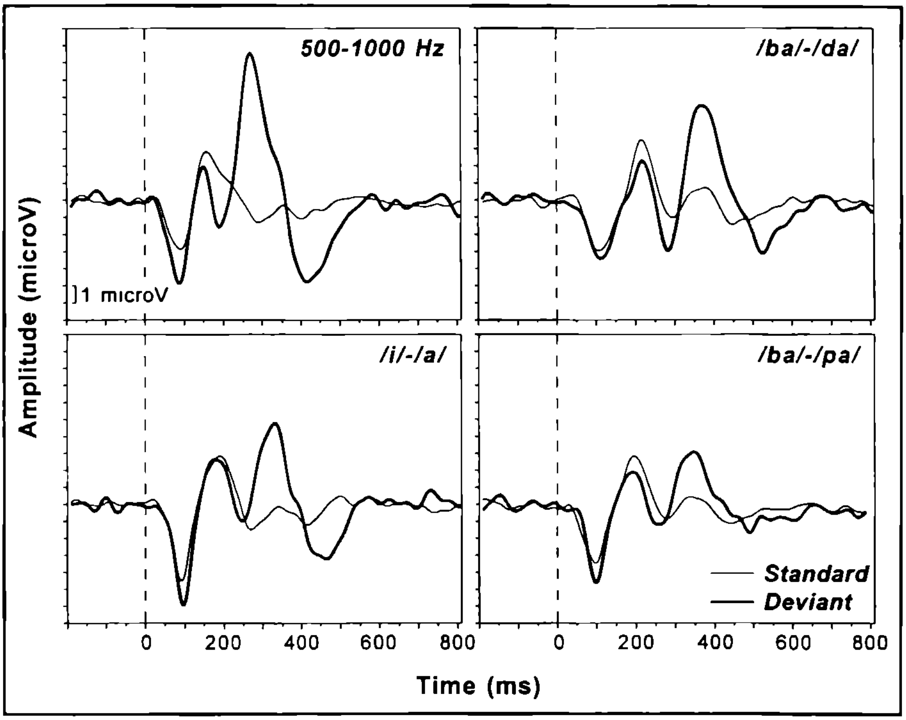


*FIGURE 7 2*
*Grand averages for the subjects with normal hearing for the four sound contrasts*

batteries[20,21] A composite score was obtained, which was the average score for a monosyllable identification test (4AFC), a spondee identification test (4AFC), a long-vowel recognition test (5AFC), and a short-vowel recognition test (4AFC). Averaging occured after correction for different chance levels The composite scores in the group of cochlear implant users varied from 52 to 100%, see Table 7.1.

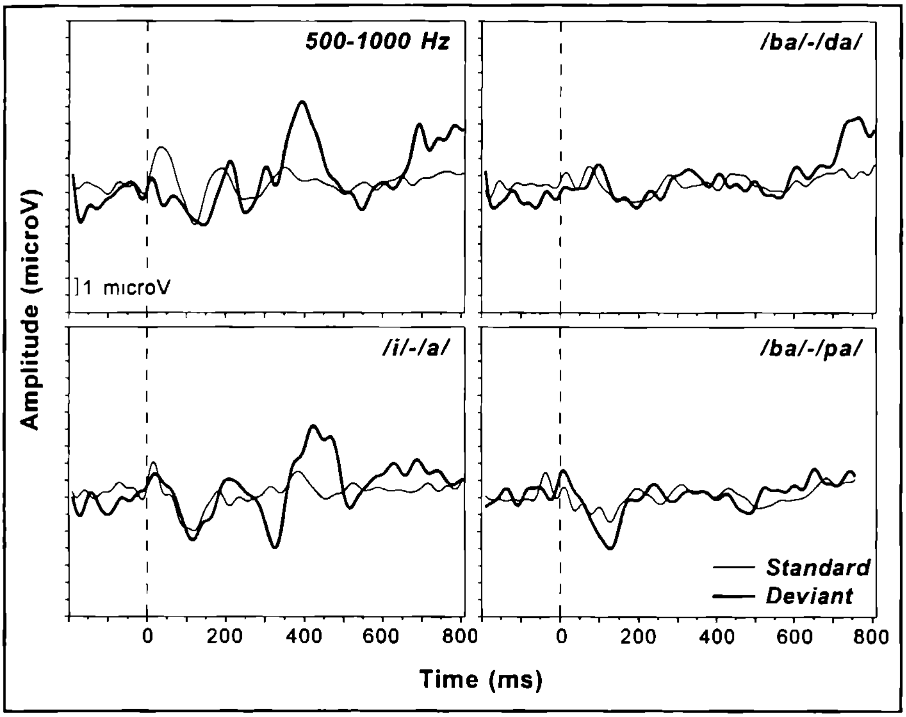


*FIGURE 7 3*
*Grand averages for the cochlear implant users for the four sound contrasts*

## Results

Firstly, results of group grand averages will be presented. Reproducible P300 peaks were found in all control subjects for all sound contrasts In Figure 7.2, the grand averages are presented for the control subjects. The amplitude of the P300 was the highest for the 500-1000 Hz sound contrast. The amplitude of the P300 for the voicing contrast /bα/-/pα/ was the lowest among the four sound contrasts.

In Figure 7.3, grand averages are presented for the cochlear implant users. A reproducible P300 peak was found for all nine patients for the 500-1000 Hz contrast and for the /i/-/a/ vowel contrast. Remarkably, though the P300 was absent in the grand average wave forms for both /bα/-/dα/ and /bα/-/pα/, P300 peaks were found for eight subjects on the /bα/-/dα/ contrast and for four subjects on the /bα/-/pα/ contrast. This will be discussed later

Difference wave forms for both the normal and the experimental group are presented in Figure 7.4. The upper line represents the wave of the cochlear implant group. The line below represents the average wave of the control group. The cochlear implant group showed prolonged average latency with smaller amplitudes for both the 500-1000 Hz and the /i/-/a/ condition. There were no distinct peaks in the grand average difference wave forms of the cochlear implant group for the consonant speech contrasts

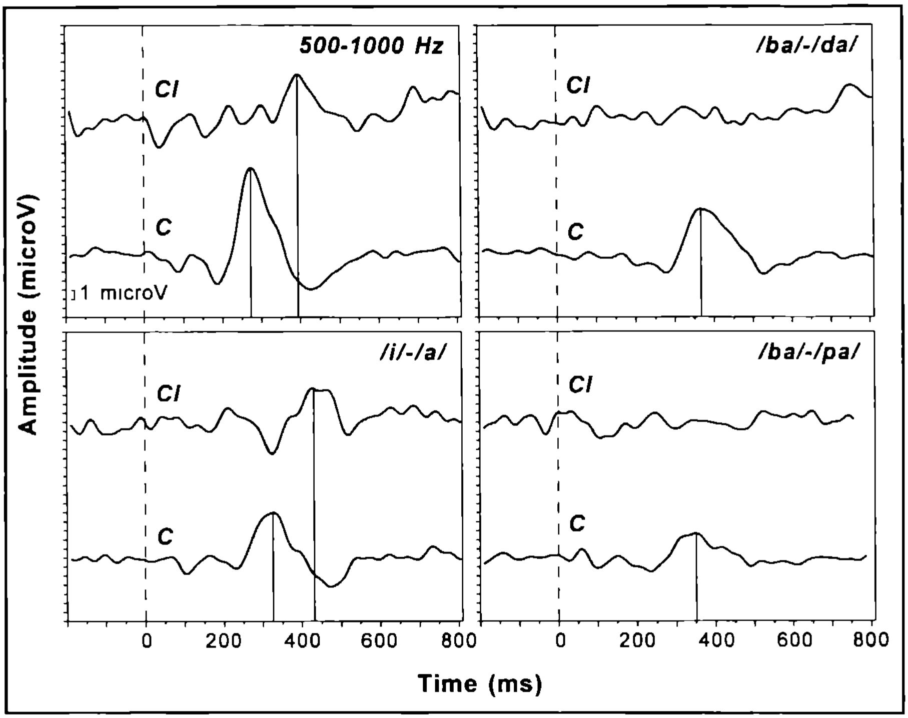


*FIGURE 7 4*
*Difference wave forms for both the control and the cochlear implant group The upper line represents the wave of the cochlear implant group The line below represents the average wave of the control group P300 peaks are marked with vertical lines*

Apart from group grand averages, individual grand averages were compared with regard to auditory late responses (N1/P2) and the cognitive response (P300) *T*-tests were performed to test for differences between means between the cochlear implant group and the control group. The *t* statistic was computed taking into account the equality or unequality of variances.[22] Under the assumption of unequal variances, the approximation of the degrees of freedom was computed using the formula of Satterthwaite.[23] In Figure 7.5, the latencies and amplitudes of N1, P2 and P300 are presented for both the cochlear impant group and the control group Latencies and amplitudes of N1 and P2 were taken from the average trace of the standard signal There were significant differences in N1 latency between both groups Prolonged latencies were found for peak N1 for the cochlear implant users for all conditions (500-1000 Hz, $t$ [1 7]=4.51, $p$= 0003; /bɑ/-/dɑ/, $t$ [9.6]=3.55, $p$=.006; /i/-/a/, $t$ [9 9]=3 96, $p$=.003; /bɑ/-/pɑ/, $t$ [9.0]=2.73, $p$=.02). Amplitudes were smaller compared to the control group for the speech sound conditions (/bɑ/-/dɑ/, *t* [17]=2.19, *p*=.04; /i/-/a/, *t* [17]=3.02, *p*=.008, /bɑ/-/pɑ/, *t* [17]=2.75, *p*=.01). The cochlear implant users showed a high amount of interindividual variation in latency values for the speech sound conditions. For all speech conditions in the cochlear implant group, the latency variation across subjects was larger compared to that in the control group (/bɑ/-/dɑ/, *F* [8,9]=9.01, *p*=.003; /i/-/a/, *F* [8,9]=7.44, *p*=.007, /bɑ/-/pɑ/, *F* [8,9]=13.83, *p*=.001).

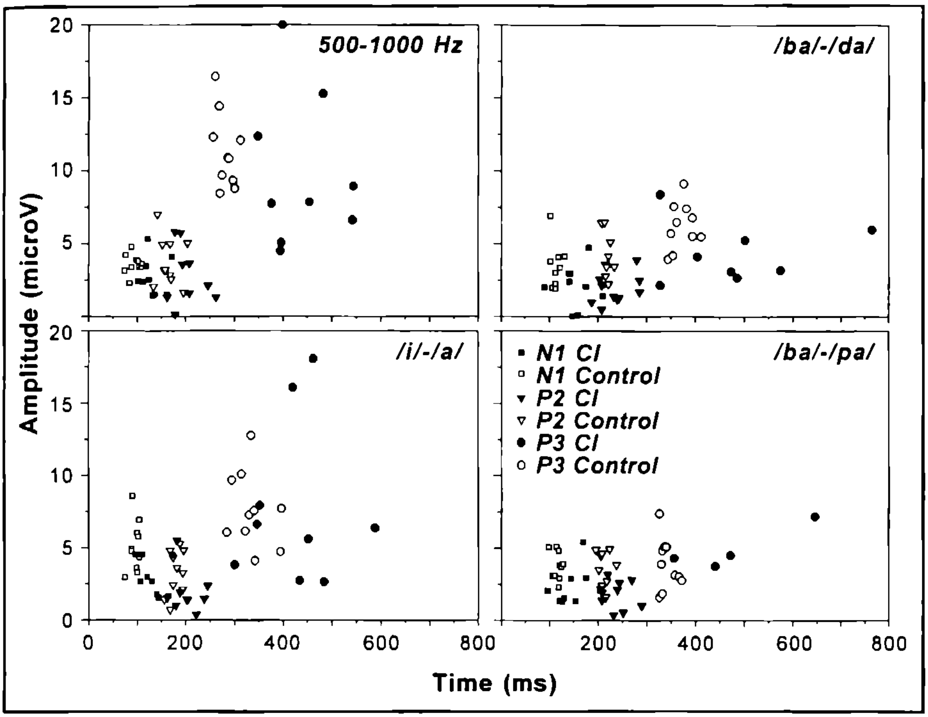


*FIGURE 7.5*
*Latencies and amplitudes for N1, P2, and P300 for both the cochlear implant group and the control group. Latencies and amplitudes for N1 and P2 were taken from the average trace of the standard signal*

For P2, the image was a bit more diffuse. Cochlear implant users showed prolonged latencies for peak P2 for all but the /bɑ/-/dɑ/ condition (500-1000 Hz, *t* [17]=3.01, *p*=.008; /i/-/a/, *t* [11.3]=2.26, *p*=.04; /bɑ/-/pɑ/, *t* [10.7]=2.77, *p*=.02). In addition, cochlear implant users showed smaller amplitudes of peak P2 for the consonants (/bɑ/-/dɑ/, *t* [17]=3.53, *p*=.003, /bɑ/-/pɑ/, *t* [17]=3.22, *p*=.005). For the speech sounds, the amount of interindividual variation in latency values for the cochlear implant group was higher than that for the control group (/bɑ/-/dɑ/, *F* [8,9]=21.40, *p*=.0001, /i/-/a/, *F* [8,9]=4.25, *p*=.04; /bɑ/-/pɑ/, *F* [8,9]=5.33, *p*=.02).

Remember that for the cochlear implant group, no P300 peak was found in the grand average wave forms of /bɑ/-/dɑ/ and /bɑ/-/pɑ/. However, individual P300 peaks were found for eight out of nine cochlear implant users for the /bɑ/-/dɑ/ contrast, and for four out of nine for the /bɑ/-/pɑ/ contrast. Prolonged latencies were found for peak P300 for the cochlear implant users for all conditions (500-1000 Hz, $t$ [8 9]=6.32, $p$= 0001; /bα/-/dα/, $t$ [7.3]=2 42, $p$=.03, /i/-/a/, $t$ [10 6]=2.95, $p$=.01, /bα/-/pα/, $t$ [3.0]=3.68, $p$=.003). In addition, cochlear implant users showed smaller amplitudes for the /bα/ /dα/ contrast ($t$ [16]=2.17, $p$=.0451). Furthermore, for all conditions in the cochlear implant group, the latency variation was much larger than that in the control group (500-1000 Hz, $F$ [8,9]=15.42, $p$= 0004, /bα/-/dα/, $F$ [7,9]=39.79, $p$=.0000; /i/-/a/, $F$ [8,9]=5.48, $p$=.02; /bα/-/pα/, $F$ [3,9]=50 91, $p$=.0000)

Summarizing, there were prolonged N1, P2 and P300 latencies in the cochlear implant group The amplitude of N1 was smaller for all speech signals The amplitude of P2 was smaller for the consonants only. The cochlear implant group showed a higher amount of interindividual variation in N1 and P2 latencies for the speech signals and in P300 latencies for all signals than that in the control group



**TABLE 7.2.**
Pearson's product-moment correlation coefficients of the p300 quality measures and speech perception ability of the cochlear implant users for the four conditions

| Condition | Latency | P300 QUALITY Amplitude | Magnitude |
|---|---|---|---|
| 500-1000 | NS | .75* | 79* |
| /i/-/a/ | NS | 82** | 81** |
| /ba/ /da/ | NS | NS | NS |
| /ba/-/pa/ | NS | NS | NS |

Note.
* = p< 05, ** = p<.01, NS = no significant correlation

P300 results were compared to subjective measures of speech perception Three measures of P300 quality were extracted: 1) latency, 2) amplitude, and 3) magnitude. In Table 7 2, P300 latency, amplitude and magnitude are compared to speech perception ability. If P300 latency is related to subjective performance, then significant negative correlation values can be expected, implying that the longer the latency, the lower the score in speech perception This was not found P300 latency did not link up with speech perception in any of the four conditions. If P300 amplitude is related to subjective performance, then significant positive correlation values can be expected, implying that the higher the amplitude, the higher the score in speech perception Significant correlations were found between P300 amplitude and speech perception ability for both the 500-1000 Hz and the /i/-/a/ condition ($r$= 75, $p$= 02; $r$= 82, $p$= 007, respectively) Typically, these were the conditions where a significant P300 in the group grand average wave form was found. Significant positive correlation values can be expected if there is a relation between P300 magnitude and speech perception, implying that the higher the magnitude, the higher the score in speech perception. Comparable to P300 amplitude, this was found for both the 500-1000 Hz and the /i/-/a/ condition ($r$=.79, $p$= 01; $r$=.81, $p$=.008, respectively) and not for the consonant contrasts

## Discussion

There were prolonged N1, P2 and P300 latencies in the cochlear implant group The amplitude of N1 was smaller for the speech signals The amplitude of P2 was smaller for the consonants In addition, the cochlear implant group showed a wider spread of N1 and P2 latencies for the speech signals and a wider spread of P300 latencies for all signals P300 latency is known to become prolonged and P300 amplitude is known to decrease as discrimination of the stimuli becomes more difficult [24,25] Hence, the implant users found it more difficult to discriminate sound contrasts than did the subjects with normal hearing

Our findings add to those of Micco et al [9] They used a /di/ /da/ speech sound contrasts for testing cochlear implant users They found P300s similar to those in subjects with normal hearing The /di/ /da/ speech contrast can be considered to represent a two dimensional physical difference The first dimension concerns the spectral character of the consonants The acoustic information corresponding to the consonant /d/ depends on vowel context In /di/, the formant transitions rise whereas in /da/ they fall The second dimension concerns the differences in center frequencies between the steady state vowel /i/ and /a/

Vowels and consonants differ in the way their are processed A steady state vowel does not contain transitional information whereas the most typical parts of consonants are the spectral and temporal transients Specific acoustic cues underlie the perception of speech Spectral transients (formant transitions) tend to be processed differently from steady state signals (e g , vowels) The role of natural auditory sensitivities seems very relevant for understanding mechanisms of speech processing [26] The auditory system is characterized by differences in discriminability across different acoustic cues Within the context of natural auditory sensitivities, Rosen and Howell[26] argued that equal physical differences need not imply equal perceptual differences In general, the rules relating acoustic events and phonetic perception are extremely complex [27]

Due to the fact that there is no simple relation between acoustic event and phonetic perception, in Micco et al [9] it was difficult to distinguish the contributions of differences in rapidly changing spectral information (consonant formant transitions) from steady state spectral information (center frequencies of vowels) in eliciting a P300 response Our procedure complemented the procedure followed by Micco et al [9] by keeping the vowel characteristics unchanged and manipulating the spectral transient in the place of articulation contrast /bα/ /dα/ and distinguishing it from the spectrally steady state vowel contrast /i/ /a/ Cochlear implant users did not show a group P300 response in the /bα/ /dα/ condition, whereas they showed a significant group P300 response in the /i/ /a/ condition We suggest that steady state vowel differences easier elicit a P300 in cochlear implant users than differences in spectrally transient information in consonants

A remarkable finding was that group grand averages of waveforms do not fully reflect individual grand averages There was no P300 response in the group average of the /ba/ /da/ contrast for the cochlear implant group, whereas in the individual averages eight out of nine subjects showed a P300 response The wide range of latency values probably had a huge smoothing effect on the group grand avera ge, resulting in a more or less flat line For evaluation of test results, therefore, it is highly advisable to check both group and individual scores.

There is a relation between P300 quality and behavioral speech perception in cochlear implant users The poorer cochlear implant performers demonstrated smaller P300 amplitudes and magnitudes than the better performers. The P300 seems to reflect behavioral speech discrimination ability. However, one should be cautious with the choice of sound contrasts. In the present study, only the 500-1000 Hz and the /i/-/a/ condition showed a relation between P300 quality and speech perception ability From studies on the mismatch negativity, it is known that between and within tonal and complex stimuli, the combination of optimal parameters seems not to be uniform [12] This means that the conclusions and suggestions derived from results of experiments using one type of stimuli, cannot a priori been generalized to experiments using another type of stimuli Although the P300 is much more robust than the mismatch negativity and the P300 reflects processing mechanisms of higher order than those involved in the mismatch negativity, validating or even assessing the success of cochlear implantation by measuring event-related potentials seems highly dependent on the type of stimulus contrasts that are used

One thing that is clear from our studies is that electrophysiological measurements are very useful in evaluating and monitoring the neural functionality of cochlear implant subjects. Objective electrophysiological data seem to be related to the subjective performance The P300 can help in fundamentally understanding the effects of electrical stimulation of the inner ear. We agree with Micco et al.[9] that it may have potential as a clinical tool for evaluating processing on a cognitive level as well as on the level of auditory discrimination This may help in adjusting and developing rehabilitation programs for cochlear implant users.



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# SUMMARY AND CONCLUSIONS



A Central Auditory Processing Disorder (CAPD) can be defined as a disorder in the process of decoding sound patterns, that cannot be explained by peripheral hearing loss. Central auditory processing disorders are not a unitary diagnostic syndrome From a behavioral point of view, subjects with CAPD are often characterized as poor listeners, easily distractable, showing short attention spans, and demonstrating poor memory for auditory information. Especially during childhood, CAPD may influence the development of aspects of language, including primary linguistic functions such as speech articulation, but also secondary linguistic functions such as reading, writing and spelling.

Classical, psychophysically oriented tests do not account for the structure and complexity of the speech signal, nor do they account for the layered complexity of the auditory system of speech perception. We would like to introduce a new approach; an approach which is based on psycholinguistic aspects of speech and speech processing as opposed to psychophysical aspects of speech and speech processing In this thesis, there are two major questions: 1) Do disorders of speech perception exist in a number of groups of subjects differing in pathological background?, and 2) Does a psycholinguistic approach to central auditory processing disorders yield new insights and knowledge about the type of the disorder?

The basic hypothesis is that a psycholinguistic approach is beneficial in assessing auditory processing disorders of speech. The central idea is that speech perception problems should be assessed with strong reference to their psycholinguistic merit.

## The background

In the first chapter, the background of the psycholinguistic approach to CAPD is presented. Speech sounds are characterized by a rather redundant acoustic organization Presentation of normal speech to assess CAPD, therefore, would yield an insensitive test. The idea behind tests for assessing CAPD is to aggravate perception conditions as to gain easier access to malfunctioning central auditory processes.

Several techniques have been applied to make tasks more difficult for the subject In general, classical clinical tests for assessing CAPD focus on aggravating speech conditions by adding sound (e g., noise in speech-in-noise tasks), subtracting information (e g., specific spectral energy in filtered speech tasks, or reducing intensity), or partitioning information (e g , in binaural fusion tasks) These tests concern psychophysical dimensions which have no direct relation to the structure of the speech signal nor a direct relation to the multi-layered character of the speech perception system Psychophysically oriented tests for CAPD, therefore, lack a psycholinguistic base

The only way speakers can reach speech rates as high as 12 to 15 phonemes per second is by allowing for overlap of articulatory gestures, resulting in coarticulated segments. The result of coarticulation is that, because of contextual influences, speech sounds rarely have physically uniform characteristics Speech sounds are "encoded " There is a marked lack of correspondence between sound and perceived phoneme This is the result of a complex encoding that makes the sounds of speech especially efficients as vehicles for the transmission of phonemic information.

Psycholinguistic reduction, as compared to psychophysical reduction, of the redundancy of speech bears on the fundamental characteristic of speech, i.e., its "encodedness." We can use the encodedness of speech as the starting point to reduce the redundancy of speech sounds, i.e. to phonetically degrade speech sounds

Central auditory integrity depends on the efficient and adequate functioning of several stages of speech coding processes. In the auditory stage, auditory features of the incoming signal are detected. Auditory processing includes a preliminary analysis and is related to auditory short-term memory.

In the phonetic stage, auditory features are mapped onto phonetic features and assembled to a phonetic string. Phonetic processing includes phonemic labeling strategies and is related to phonetic memory.

In this thesis, auditory and phonetic processing in groups of subjects differing in pathological background will play a central role. We will make use of a psycholinguistic reduction of the redundancy of the speech materials to assess auditory and phonetic processing. Psycholinguistically oriented reduction of the redundancy will appear on two levels: a) inter-feature level: by utilizing speech sound continua, i.e., series of speech sounds where one phoneme gradually changes into another phoneme by manipulation of a specific phonetic cue, and b) intra-feature level: the character of a phonetic feature is degraded in such a way that phonemic integrity is only just preserved.

In our opinion, all subjects who demonstrate language or language related problems are suspect for having CAPD of speech. In this thesis, several subject groups are examined for central auditory processing disorders These include children with a) developmental dyslexia, b) general articulation problems, c) a prolonged history of otitis media with effusion during early childhood, d) general language problems, e) a diagnosis of developmental apraxia of speech, f) articulation problems of apraxic nature, and g) adults with a cochlear implant.

## The studies

### chapter 2

In chapter 2, focus is on speech perception in children with developmental dyslexia. In short, these children demonstrate problems with reading, spelling and writing, despite normal intelligence. It is hypothesized that when the internal representations of speech sounds is weak, problems of dyslexic nature may arise. Auditory and phonetic perception of the features place-of-articulation and voicing was examined, and compared with the perception in two control groups of children (age-matched and matched on reading level). It appeared that children with developmental dyslexia exhibited problems with discriminating small speech sound differences for both place-of-articulation and voicing. This suggests central auditory processing disorders which are more auditory than phonetic in nature. The validity of the findings was confirmed by the fact that there existed a strong quantitative relation between reading and spelling problems on the one hand and perceptual problems on the other.

### chapter 3

In chapter 3, phonetic processing of place-of-articulation in children and adolescents with general articulation problems is investigated. Articulation problems may be associated with problems in perception. Speech material consisting of words with variable formant transition durations was presented. In general, children with articulation problems demonstrated a lower quality in phonetic processing than the control subjects. This applied for both the words with long and the words with short formant transition durations.

### chapter 4

In chapter 4, perception of the feature voicing in children with a history of otitis media with effusion (OME) with and without language impairments is examined Auditory deprivation of acoustic information during OME periods at early age may influence the development of central auditory and phonetic structures. Indeed, this appeared to be true. Children with a history of OME showed problems with both auditory and phonetic processing of voicing. These problems emerged, irrespective of possible additional general language impairment, though a language impairment did not deteriorate the situation. Both early OME and language impairment were related to perceptual problems of auditory and phonetic nature

### chapter 5 / chapter 6

In chapter 5 and 6, children with a diagnosis of developmental apraxia of speech and children with speech perception problems of apraxic nature are tested on the perception of consonants (the feature place-of-articulation) and vowels, respectively Developmental apraxia of speech is a neurogenic motoric articulation disorder and can be characterized by a reduced capacity to program articulatory gestures en sequencing movements for producing speech. The hypothesis was that this production disorder has a perceptual component. The hypothesis was confirmed. Auditory processing of children with developmental apraxia of speech was affected. There was a specific relation between the perception and production of place-of-articulation errors In a follow-up study in children with similar articulation problems, the perception of vowels also appeared to be affected The effect in this group of children was remarkably strong Children with speech production problems of apraxic nature demonstrated difficulties for auditory as well as phonetic processing of vowels In addition, the perceptual tasks showed a high clinical value.

chapter 7

In chapter 7, stimuli previously used in studies assessing central auditory processing problems in children with developmental apraxia of speech and developmental dyslexia are presented to adult cochlear implant users. Electrophysiological methods were used to study the integrity of the central auditory system. Central auditory integrity is supposed to play a crucial role in explaining the variation in cochlear implant benefit. Cochlear implant users demonstrated delayed processing of sounds and speech signals. In addition, electrophysiological indices of auditory processing were related to general results of speech perception performance.



## Major questions, major answers

*1) Do disorders of speech perception exist in a number of groups of subjects differing in pathological background?*

The answer is yes: a) Children with developmental dyslexia demonstrate problems with discriminating small speech sound differences for both the place of-articulation and the voicing feature. This suggested central auditory processing disorders which are more auditory than phonetic in nature; b) Children with articulation problems demonstrated a poorer phonetic processing of formant transitions than children without articulation problems; c) Children with a history of OME showed problems with both auditory and phonetic processing of voicing. These problems emerged, irrespective of possible additional general language impairment. Both early OME and language impairment were related to perceptual problems of auditory and phonetic nature, d) Auditory discrimination of the place-of-articulation feature of children with developmental apraxia of speech was affected suggesting problems with auditory processing; e) In addition, children with speech production problems of apraxic nature demonstrated difficulties for auditory as well as phonetic processing of vowels; and f) Cochlear implant users demonstrated delayed processing of sounds and speech signals.

In short, specific language and speech disorders, which in general have been described according to symptoms that are most catching for eye and ear, turn out to have a significant perceptual component.

*2) Does a psycholinguistic approach to central auditory processing disorders yield new insights and knowledge about the type of the disorder?*

Again, the answer is yes. A psycholinguistic approach has proven to tap into aspects of central auditory processing which are strongly related to psycholinguistic aspects of both the speech signal and the speech information processing system In all the groups that were studied in this thesis, central auditory processing disorders of psycholinguistic nature were seen.

A psycholinguistic approach can demonstrate perception problems associated with a variety of speech and language disorders The value of a psycholinguistic approach to central auditory processing disorders for differential diagnosis of speech and language disorders has yet to be established

## Speech processing levels



The data in this thesis are consistent with the suggestion that subjects with primary and secondary linguistic problems are significantly impaired in specific aspects of auditory and phonetic analysis. These lower-level auditory and phonetic disabilities may affect the ability to perform higher-level perceptual, cognitive, and linguistic tasks. For example, learning to speak, read and spell presupposes internalized phonemic representations acquired through experience with speech. If stable speech sound representations have not been developed, problems in speaking, reading and spelling may arise. Speech perception problems may then be viewed as complicating the conditions for adequate development of speech and language ability.

According to a dual-coding structure of auditory and phonetic processing, it is not likely for phonetic identification to be normal while auditory discrimination is disturbed. The question is whether or not phonetic identification can develop with problems of auditory processing. A more flexible model than a hierarchical mapping process from the acoustic to phonetic stages seems needed. The results of studies in this thesis support a structure for speech processing with an auditory stage and a phonetic stage partly allowing for stage-independent output. This is a structure in which the integrity of phonetic processing is not totally dependent on the outcome of auditory processing.

An alternative explanation for the fact that discrimination problems can exist without identification problems could lie in subject strategy factors. Subjects may vary in cue weighting strategy. Dysfunctional speech perception may be determined by the process of attributing different (yet valid and adequate) weights to acoustic cues in the process of categorization as compared to the cues on which discrimination was based. This would allow discrimination performance to be affected while identification was not. Such a viewpoint is highly compatible with the fuzzy logical model of speech perception This viewpoint also seems compatible with the concepts of the WRAPSA model (Word Recognition and Phonetic Structure Acquisition) Selective attention within a set of intraphonetic cues seems likely to play a role in phonetic processing. It is possible that cues playing a minor role are weighted less in the identification proces. Thus, problems with discrimination of these minor cues may not have as much importance for the identification process as problems in discrimination of more important speech cues. This standpoint seems highly plausible to us because it accounts for the multidimensionality of the speech signal as well as the multidimensionality of the speech processing system

## Clinical interest

In this thesis, a limited number of various speech features have been used to assess perception processes (e.g., place-of-articulation cues, variable formant transition cues, cooperating and conflicting voicing cues).

Psycholinguistic assessment of CAPD may have value as a clinical tool for evaluating auditory and phonetic processing. Such a tool may consist of a set of perception tasks based on speech tokens with variable consonant and vowel structures and variable formant transition durations (as to cover all speech sounds and degrees of sensitivity in auditory and phonetic processing). This approach may offer useful information about central auditory processing with an emphasis on subphonemic psycholinguistic aspects of speech perception. Classical central auditory tests (based on the principle of reducing the redundancy on psychophysical dimensions, e.g , speech-in-noise recognition, binaural fusion tasks, filtered speech recognition, time-altered speech recognition) are of great importance for assessing general speech perception problems. The results in this thesis, however, advocate supplementing the classical test battery with perceptual tasks focusing on specific psycholinguistic aspects of speech perception.

The system of auditory and phonetic analysis is characterized by its plasticity Previous research has shown that it can be trained. This offers the opportunity to adjust and develop rehabilitation programs for subjects with problems in central auditory processing. In what specific way this should be done is an important point for future research

## Social relevance

As mentioned earlier, from a behavioral perspective, people with central auditory processing disorders are qualified as bad listeners, easily distractable, short attention spans, and with a bad memory for auditory information. Unfortunately, these symptoms do not always clearly manifest themselves, and are often not tagged as being a symptom of central auditory dysfunctionality. Making a diagnosis of central auditory processing disorders is complicated by two factors (a) perceptual disorders often underly other disorders (e.g., articulation problems, dyslexia, attention deficits, hyperactivity), and (b) the effects of central auditory processing disorders can be found at various levels (e.g , social, emotional, didactic). Therefore, it is of great importance that when having suspicion of central auditory problems, these are approached from several points of view. A psychophysical angle is indispensable, though not ultimately satisfying. A psycholinguistic angle seems indispensable, though also not ultimately satisfying. A combination of both is promising This thesis describes one of many ways to study the psycholinguistics of central auditory processing disorders. In order to gain insight not only in making diagnosis but also in the development of therapy and intervention programmes, it is necessary to follow a multidisciplinary approach of central auditory processing disorders. This is an approach that emphasizes psychophysical and psycholinguistic as well as medical (neurologic, motoric, etc.) and social aspects.

# SAMENVATTING EN CONCLUSIES

Centraal auditieve problemen betreffen de decodering van complexe geluidspatronen, waarbij er geen sprake is van perifeer gehoorverlies. Centraal auditieve problematiek is multidimensioneel. Vanuit een gedragsmatig perspectief worden mensen met centraal auditieve problemen gekarakteriseerd als slechte luisteraars en snel afleidbaar Ze hebben een korte aandachtspanne en een slecht geheugen voor auditieve informatie. Vooral in de kinderjaren kunnen centraal auditieve problemen de ontwikkeling beinvloeden van bepaalde aspecten van taal. Dit geldt voor primaire linguistische functies zoals spraakarticulatie, maar ook voor secundaire linguistische functies zoals lezen, schrijven, en spellen

Klassieke, psychofysisch georienteerde tests houden nauwelijks rekening met de structuur en de complexiteit van het spraaksignaal en houden geen rekening met de gelaagde complexiteit van het auditieve systeem van spraakverwerking. Wij introduceren een nieuwe benadering; een benadering die gebaseerd is op psycholinguistische (en niet op psychofysische) aspecten van spraak en spraakverwerking In dit proefschrift worden twee centrale vragen aan de orde gesteld: 1) Is er sprake van spraakwaarnemingsproblemen in bepaalde pathologische groepen?, en 2) Verschaft een psycholinguistische benadering van centraal auditieve stoornissen nieuwe inzichten en kennis over het type pathologie?

De basishypothese is dat een psycholinguistische aanpak waarde heeft voor het beoordelen van van centraal auditieve spraakwaarnemingsproblemen De centrale idee is dat spraakwaarnemingsproblemen moeten worden beoordeeld op hun psycholinguistische inhoud.

## De achtergrond

In het eerste hoofdstuk wordt de achtergrond van de psycholinguistische benadering van centraal auditieve stoornissen gepresenteerd. Het spraaksignaal wordt gekenmerkt door een grote akoestische redundantie. Een centraal auditieve test die gebruik maakt van normale spraak is niet sensitief genoeg. De gedachte achter veel centraal auditieve tests is het bemoeilijken van spraakverstaan waardoor stoornissen eventueel sneller aan de oppervlakte komen.

Er zijn meerdere technieken om perceptuele taken moeilijker te maken voor de luisteraar. De meeste klassieke tests zijn gebaseerd op een reductie van de redundantie van het spraaksignaal door toevoeging van geluid (bijvoorbeeld: ruis), aftrekking van informatie (bijvoorbeeld: door middel van filtering of intensiteitsreductie), of verdeling van informatie (bijvoorbeeld binaurale fusie taken) Deze tests betreffen psychofysische dimensies die geen directe relatie hebben met de structuur van het spraaksignaal noch met het gelaagde complexiteit van het auditieve systeem van spraakverwerking Psychofysisch georienteerde tests voor het meten van centraal auditieve problemen ontberen een psycholinguistische basis

De enige manier waarop mensen spreeksnelheden van 12 tot 15 fonemen per seconde kunnen halen is door overlapping van articulatorische bewegingen Dit resulteert in gecoarticulateerde spraak. Het resultaat van coarticulatie is dat spraak klanken zelden fysiek uniforme karakteristieken hebben Spraakgeluiden zijn "gecodeerd " Er is een aanmerkelijk gebrek aan overeenkomst tussen spraakgeluid en de waargenomen spraakklank. Dit is het resultaat van een complex coderingsssyteem dat spraakgeluiden zeer efficient maakt als middel voor de transmissie van fonemische informatie.

In tegenstelling tot psychofysische reductie van de redundantie heeft psycholinguistische reductie betrekking op de fundamentele karakteristiek van gecodeerdheid van spraak We kunnen de gecodeerdheid van spraak als uitgangspunt nemen voor de reductie van de redundantie van spraakgeluiden oftewel de fonetische degradatie van spraakklanken

De integriteit van het centraal auditieve systeem is afhankelijk van het efficient en adequaat functioneren van verschillende stappen in het systeem van spraakdecodering In de auditieve fase van spraakverwerking worden verschillende parameters uit het akoestisch signaal geextraheerd. In deze fase vindt een preliminaire analyse plaats van het spraaksignaal Informatie wordt opgeslagen in het auditieve korte-termijn geheugen In de fonetische fase, daarentegen, worden de parameters gecombineerd en wordt een betekenisvolle eenheid gevormd het foneem. Fonetische waarneming behelst het toepassen van fonemische labellingsstrategieen Informatie wordt opgeslagen in het fonetische korte-termijn geheugen.

In dit proefschrift spelen auditieve en fonetische waarneming bij verscheidene pathologische doelgroepen een centrale rol. Voor het meten van auditieve en fonetische waarnemingsprocessen zal gebruik worden gemaakt van een psycholinguistische reductie van de redundantie van het spraakmateriaal. Psycholinguistische reductie van redundantie komt voor op twee nivo's (a) 'inter-feature' nivo: door gebruik te maken van spraakcontinua, een serie spraaksignalen waar een foneem langzaam verandert in een ander foneem door middel van manipulatie van een specifiek fonetisch kenmerk, en (b) 'intra-feature' nivo. het karakter van een fonetisch kenmerk word dusdanig gedegradeerd dat fonemische integriteit ternauwernood gehandhaafd blijft

Naar onze mening is iedereen met taal of aan taal gerelateede problemen eventueel gevoelig voor centraal auditieve spraakwaarnemingsproblemen. In dit proefschrift worden verscheidene doelgroepen getest op centraal auditieve problemen, waaronder kinderen met (a) een ontwikkelingsdyslexie, (b) algemene articulatieproblemen, (c) een achtergrond van langdurige otitis media met effusie in de peuterleeftijd, (d) algemene taalproblemen, (e) een diagnose van verbale ontwikkelingsdyspraxie, (f) articulatie problemen van dyspraktische aard, en (g) volwassenen met een cochleaire implantaat.

hoofdstuk 2

In hoofdstuk 2 wordt ingegaan op spraakverwerking bij kinderen met een ontwikkelingsdyslexie In het kort hebben deze kinderen problemen met lezen, spellen en schrijven, ondanks een normale intelligentie Verondersteld wordt dat indien de interne representatie van spraakklanken zwak is, problemen van dyslectische aard kunnen optreden Auditieve en fonetische waarneming van de kenmerken plaats-van-articulatie en stemhebbendheid werd getest en vergeleken met de waarneming bij twee groepen controle kinderen (matching op leeftijd en leesnivo) Het bleek dat kinderen met een ontwikkelingsdyslexie problemen hadden met het discrimineren van kleine spraakklankverschillen op zowel het kenmerk plaats-van-articulatie als stemhebbenheid Dit duidt op een centraal verwerkingsprobleem dat eerder op het auditieve vlak dan op het fonetische vlak ligt De validiteit van deze bevindingen werd ondersteund door het feit dat er een sterke quantitatieve relatie was tussen enerzijds de lees en spellingsstoornis en anderzijds de perceptuele stoornis.

hoofdstuk 3

In hoofdstuk 3 word de fonetische verwerking van plaats-van-articulatie bij kinderen en adolescenten met algemene articulatieproblemen bestudeerd. Articulatieproblemen zouden gepaard kunnen gaan met problemen in de spraakperceptie Spraakmateriaal bestaande uit woorden met variabele formanttransitieduren werd gepresenteerd. In het algemeen vertoonden de subjecten met articulatieproblemen een lagere kwaliteit van fonetische waarneming dan de controle subjecten. Dit gold voor zowel de woorden met korte als met lange formanttransitieduren.

hoofdstuk 4

In hoofdstuk 4 worden kinderen met otitis media met effusie (OME) in de peuterleeftijd met of zonder algemene taalproblemen onderzocht op de verwerking van het spraakkenmerk stemhebbenheid Auditieve deprivatie van akoestische informatie gedurende de OME periodes op vroege leeftijd zou van invloed kunnen zijn op de ontwikkeling van centraal auditieve en fonetische structuren Dit bleek inder daad zo te zijn Kinderen met vroege OME hadden problemen met zowel de auditieve als de fonetische verwerking van het kenmerk stemhebbendheid. Deze problemen traden op ongeacht een eventuele bijkomende algemene taalachterstand, maar een algemene taalachterstand verergerde de problemen niet Zowel vroege OME als het hebben van een algemene taalachterstand bleek verbonden te zijn met perceptuele problemen van auditieve en fonetische aard.

hoofdstuk 5 / hoofdstuk 6

In hoofdstuk 5 en 6 worden kinderen gediagnostiseerd als zijnde verbaal dyspractisch en kinderen met spraakproblemen van dyspractische aard getest op de waar neming van respectievelijk consonanten (het kenmerk plaats-van-articulatie) en klinkers. Verbale ontwikkelingsdyspraxie is een neurogene motorische articulatiestoornis en wordt gekenmerkt door een verminderde capaciteit tot de programmering van articulatiebewegingen en de opeenvolging van de bewegingen voor het produceren van spraak. Het idee was dat aan deze productie problemen een perceptuele component verbonden zou zijn Er bleken inderdaad verwerkingsproblemen te zijn De auditieve verwerking van plaats van-articulatie was aangetast Er was een speci fieke relatie tussen de perceptie en productie van plaats van articulatie kenmerken In een vervolgstudie bij kinderen met soortgelijke articulatieproblemen bleek dat ook de verwerking van klinkers was aangetast Het effect was bij deze kinderen zelfs aanmerkelijk sterker Kinderen met articulatieproblemen van dyspractische aard vertoonden problemen met zowel de auditieve als de fonetische verwerking van klinkers Bovendien bleek de klinische waarde van de perceptuele taken aanzienlijk



hoofdstuk 7

In hoofdstuk 7 worden stimuli die eerder gebruikt zijn in het benaderen van centraal auditieve problemen bij verbaal dyspractische kinderen en dyslectische kinderen aangeboden aan volwassen dragers van een cochleaire implant Elektrofysiologische methoden werden gebruikt om de integriteit van het centraal auditieve systeem te onderzoeken Centraal auditieve integriteit kan van belang zijn in het verklaren van de variatie in het succes van cochleaire implantatie Cochleaire implant gebruikers vertoonden veelal een vertraagde verwerking van geluid en spraaksignalen Bovendien bleek dat elektrofysiologische indices van centraal auditief functioneren gerelateerd waren aan algemene resultaten met betrekking tot spraakwaarneming

## Belangrijke vragen, belangrijke antwoorden

*1) Is er sprake van spraakwaarnemingsproblemen in bepaalde pathologische groepen?*

Het antwoord is bevestigend a) Kinderen met een ontwikkelingsdyslexie problemen hadden met het discrimineren van kleine spraakklankverschillen op zowel het kenmerk plaats van-articulatie als stemhebbenheid Dit duidt op een centraal verwerkingsprobleem dat eerder op het auditieve vlak dan op het fonetische vlak ligt, b) Kinderen met articulatieproblemen toonden een lagere kwaliteit van fonetische waarneming van formanttransities dan kinderen zonder articulatieproblemen, c) Kinderen met vroege OME hadden problemen met zowel de auditieve als de fonetische verwerking van het kenmerk stemhebbendheid Deze problemen traden op ongeacht een eventuele bijkomende algemene taalachterstand Zowel vroege OME als het hebben van een algemene taalachterstand bleek verbonden te zijn met perceptuele problemen van auditieve en fonetische aard, d) De auditieve discriminatie van het kenmerk plaats van-articulatie bij kinderen met een verbale ontwikkelings dyspraxie was aangetast, duidende op problemen het auditieve stadium van spraakverwerking, e) Bovendien, bleek dat bij kinderen met soortgelijke articulatie problemen zowel de auditieve als de fonetische verwerking van klinkers was aangetast, en f) Cochleaire implant gebruikers vertoonden veelal een vertraagde verwerking van geluid en spraaksignalen

Samenvattend, specifieke taal- en spraakstoornissen, die in het algemeen worden beschreven aan de hand van meest in het oog en oor vallende symptomatologie, hebben een substantiele perceptuele component

*2) Verschaft een psycholinguistische benadering van centraal auditieve stoornissen nieuwe inzichten en kennis over het type pathologie?*

Opnieuw is het antwoord bevestigend. Een psycholinguistische benadering legt onmiskenbaar de nadruk op aspecten van centraal auditieve processen die sterk gerelateerd zijn aan psycholinguistische aspecten van zowel het spraaksignaal als het systeem van spraakverwerking In alle doelgroepen uit dit proefschrift werden centraal auditieve stoornissen gezien van psycholinguistische aard.

Een psycholinguistische benadering kan perceptuele problemen aantonen in een aantal spraak en taalstoornissen. De waarde van een psycholinguistische benadering voor differentiaal diagnostiek van taal- en spraakstoornissen moet echter nog vastgesteld worden.



## Nivo's van spraakwaarneming

De data in dit proefschrift sluiten aan bij de idee dat mensen met primaire of secundaire taalproblemen problemen hebben met specifieke aspecten van auditieve en fonetische waarneming. Deze lagere-orde auditieve and fonetische problemen kunnen het uitvoeren van hogere-orde perceptuele, cognitieve, en linguistische taken beinvloeden Bijvoorbeeld, het leren van spreken, lezen en spellen veronderstelt geinternaliseerde fonemische representaties verworven door ervaring met spraakgeluid Als stabiele spraakklankrepresentaties niet zijn ontwikkeld kunnen problemen in het spreken, lezen, en spellen voorkomen. Spraakwaarnemingsproblemen bemoeilijken dan de condities voor een adequate ontwikkeling van spraak- en taalvermogens.

Volgens een twee-fase structuur van auditieve en fonetische waarneming is het niet waarschijnlijk dat fonetische identificatie normaal terwijl auditieve discriminatie afwijkend is. De vraag is of fonetische identificatie zich al dan niet kan ontwikkelen als er problemen zijn in de auditieve discriminatie Een meer flexibel model dan een hierarchisch model voor de overgang van akoestische informatie naar fonetische informatie lijkt gepast. De resultaten van de studies in dit proefschrift ondersteunen een structuur van spraakwaarneming waar de auditieve en fonetische fase fase-onafhankelijke output leveren Dit is een structuur waarin de integriteit van de fonetische fase niet helemaal afhankelijk is van de resultaten van de auditieve analyse.

Een alternatieve verklaring voor het feit dat problemen in de discriminatie kunnen voorkomen zonder dat sprake is van problemen in de identificatie ligt in subject-strategie factoren Luisteraars kunnen verschillen in de manier waarin ze subfonemische spraakkenmerken waarderen en wegen Afwijkende spraakwaarneming kan veroorzaakt zijn door een proces dat verschillende (maar valide en adequate) gewichten toekent aan akoestische kenmerken tijdens de categorisatie in vergelijking tot aan de kenmerken waarop discriminatie is gebaseerd. Zo zou het discriminerend vermogen kunnen zijn aangetast terwijl het identificerend vermogen intact is. Dit standpunt sluit goed aan bij het fuzzy logical model van spraakwaarneming Dit standpunt lijkt ook goed aan te sluiten bij het concept van het WRAPSA model (Word Recognition and Phonetic Structure Acquisition). Selectieve aandacht in een set van intrafonetische kenmerken speelt waarschijnlijk een rol in de fonetische waarneming Het is mogelijk dat kenmerken die een ondergeschikte rol spelen een laag gewicht hebben in het identificatieproces. Hierdoor kunnen problemen in de discriminatie van deze ondergeschikte kenmerken van minder belang zijn voor het identificatieproces dan problemen in de discriminatie van meer bovengeschikte kenmerken. Dit standpunt lijkt ons zeer plausibel daar het recht doet aan de multidimensionaliteit van het spraaksignaal alsook de multidimensionaliteit van het systeem van spraakverwerking.



## Klinisch belang

In dit proefschrift zijn een beperkt aantal verschillende spraakkenmerken gebruikt om waarnemingsprocessen te beoordelen (o.a., plaats-van-articulatie kenmerken, variable formanttransitie kenmerken, samenwerkende en tegenwerkende stemhebbendheid kenmerken).

Een psycholinguistische beoordeling van centraal auditieve waarnemingsproblemen kan klinisch waardevol zijn om auditieve en fonetische processen te evalueren Een klinisch instrument zou kunnen bestaan uit een set van perceptie-taken gebaseerd op spraakmateriaal met variabele consonant en klinker structuren en variabele formant transitie duren (om het arsenaal aan spraakklanken te dekken en verschillen in auditieve en fonetische sensitiviteit aan te kunnen tonen). Deze benadering zou nuttige informatie kunnen geven over de centraal auditieve waarneming met de nadruk op subfonemische psycholinguistische aspecten van spraakwaarneming. Klassieke centraal auditieve tests (gebaseerd op het principe van psychofysische redundantie-reductie, bijvoorbeeld spraak-in-ruis taken, binaurale fusie taken, gefilterde spraak taken, gecomprimeerde spraak taken) zijn van groot belang voor de beoordeling van algemene spraakwaarnemingsproblemen. De resultaten uit dit proefschrift bepleiten echter een aanvulling op de klassieke testbatterij in de vorm van perceptuele tests die meer gericht zijn op specifieke psycholinguistische aspecten van spraakwaarneming.

Het systeem van auditieve en fonetische analyse wordt gekenmerkt door zijn plasticiteit. Eerder onderzoek heeft aangetoond dat het 'trainbaar' is. Dit geeft de mogelijkheid tot bijstelling en ontwikkeling van revalidatieprogramma's voor mensen met centraal auditieve spraakwaarnemingsproblemen. De specifieke manier waarop dit gedaan zou moeten worden is een belangrijk punt voor toekomstig onderzoek

## Maatschappelijke relevantie

Zoals gezegd, vanuit een gedragsmatig perspectief worden mensen met centraal auditieve problemen gekarakteriseerd als slechte luisteraars, snel afleidbaar, met korte aandachtspanne, en met een slecht geheugen voor auditieve informatie Ongelukkigerwijs zijn deze symptomen niet altijd duidelijk zichtbaar en worden vaak niet aangemerkt als zijnde een symptoom van centraal auditief dysfunctioneren Diagnose-stelling van centraal auditieve stoornissen wordt bemoeilijkt door twee factoren (a) perceptuele stoornissen gaan veelal gepaard met andere stoornissen (articulatieproblemen, dyslexie, concentratie problemen, hyperactiviteit, etc.), en (b) de effecten van centraal auditieve stoornissen kunnen op vele terreinen liggen (sociaal, emotioneel, didactisch, etc.) Het is daarom van belang dat daar waar een centraal auditieve stoornis verwacht wordt, deze benaderd wordt vanuit meerdere invalshoeken Een psychofysische invalshoek is onontbeerlijk, echter niet alleenzaligmakend. Een psycholinguistische invalshoek lijkt onontbeerlijk, is echter ook niet alleenzaligmakend. Een combinatie van beide is veelbelovend. Dit proefschrift beschrijft een van de mogelijkheden om psycholinguistisch onderzoek te doen naar centraal auditieve stoornissen Teneinde niet alleen inzicht te krijgen in diagnose-stelling maar ook in de ontwikkeling van therapie en middelen tot interventie, is het noodzaak een multidisciplinaire aanpak van centraal auditieve stoornissen te volgen Dit is een aanpak die zowel de psychofysische en psycholinguistische, als ook andere medische (neurologische, motorische, etc.) en maatschappelijke aspecten benadrukt.

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**Snik, A., Groenen, P., Brokx, J., & Van den Broek, P.** (1996) Speech perception of prelingually deaf children using a cochlear implant *ASHA abstract book*, 120



**Parts of the results have been presented at:**

- American Speech-Language-Hearing Association (ASHA) Annual Convention, San Antonio, Texas, USA, november 20-23, 1992
- American Speech Language-Hearing Association (ASHA) Annual Convention, Anaheim, California, USA, november 19-22, 1993
- American Speech Language Hearing Association (ASHA) Annual Convention, New Orleans, Louisiana, USA, november 17-21, 1994
- American Speech-Language Hearing Association (ASHA) Annual Convention, Seattle, Washington, USA, november 21 24, 1996
- XIIth International Congress of Phonetic Sciences, Aix en Provence, France, Augustus 19-24, 1991
- Zestiende minisymposium over lezen Lezing IWTS, Nijmegen, the Netherlands, 22 april, 1993
- Zentrale Horstorungen, 7 Multidisziplinares Kolloquium der Geers Stiftung Bonn, Deutschland, 14 15 Marz, 1994
- International Clinical Phonetics and Linguistics Association, Symposium #3, Helsinki, Finland, november, 1993
- International Clinical Phonetics and Linguistics Association, Symposium #4, New Orleans, Louisiana, USA, november 14-16, 1994.
- International Clinical Phonetics and Linguistics Association, Symposium #6, Nijmegen, The Netherlands, october 13-15, 1997.
- XIV Biennial Symposium IERASG, Lyon, France, 27 31 august, 1995
- European Congres on Audiology Noordwijkerhout, the Netherlands, 19-23 maart, 1995
- 3rd European Conference on Audiology, Prague, june 18-21, 1997
- KNO vergadering, Groningen, the Netherlands, 12/13 mei, 1995
- International congress on cochlear implants Paris, France, april 27-29, 1995
- V International Cochlear Implant Conference, New York, New York, USA, may 1 3, 1997
- Audiologisch Centrum Eindhoven, 1990
- Martinus van Beekschool, Nijmegen, the Netherlands, 1991, 1995
- Interfacultaire Werkgroep Taal en Spraak, Max Planck Instituut, Nijmegen, the Netherlands, 1992
- The linguistic circle of Edinburgh, University of Edinburgh, Scotland, 1994
- Northwestern University, Evanston, Illinois, USA, 1994, 1995
- Haskins Laboratories, Yale University, New Haven, Connecticut, USA, 1994
- NWO-Stichting gedragswetenschappen OG Taal en Geheugen Rijksuniversiteit Utrecht the Netherlands, 1995

- Werkgroep Neurale Bronkarakterisering, Nijmegen, the Netherlands, 1995
- WAP Werkverband Amsterdamse Psycholinguisten, Universiteit van Amsterdam, the Netherlands, 1995
- Werkgroep Neurofysica, Lunteren, the Netherlands, 1996
- University of California at Davis, Department of Neurology and Center for Neuroscience, Martinez, California, USA, 1996

# CURRICULUM VITAE

Paul Groenen werd geboren op 15 april 1966 in Horst (Lb) Na het doorlopen van de basisschool in zijn geboortedorp, werd in 1984 het diploma VWO-Atheneum B gehaald aan het Boschveldcollege te Venray. Na jarenlang de wens te hebben gehad naar de kunstacademie te gaan werd in datzelfde jaar ternauwernood en impulsief gekozen voor een opleiding Psychologie aan de Katholieke Universiteit Nijmegen Een terechte keuze naar later bleek. Binnen de hoofdrichting Psychologische Funktieleer liep hij een wetenschappelijke stage onder begeleiding van Dr Dirk Jan Povel binnen het project "de visuele spraakafbeelder" Doel van het project was de ontwikkeling en implementatie van visuele hulpmiddelen voor het spreekonderricht aan dove kinderen In december 1989 werd het doctoraal examen gehaald met het predikaat 'met genoegen.' Zijn scriptie "Dimensionele reductie van klinkerspectra" werd door het college van decanen van de Katholieke Universiteit Nijmegen verkozen als beste scriptie van 1989 van de faculteit Sociale Wetenschappen. Op voordracht van het bestuur van de faculteit der Sociale Wetenschappen werd hem in mei 1990 de Universitaire Studieprijs toegekend De eerste maanden van 1990 werkte hij als student-assistent voor het eerder genoemde project

In april 1990 werd hij door de Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO) geplaatst aan de afdeling Medische Psychologie van het Academisch Ziekenhuis Nijmegen en gedetacheerd aan de afdelingen Keel-, Neus-, en Oorheelkunde en het Interdisciplinair Kinderneurologisch Centrum aldaar, en werd begonnen met het door NWO-Psychon gefinancierde project "Onderzoek naar spraakwaarnemings-processen van subfonemische eigenschappen bij kinderen met een centraal auditieve stoornis " Van dit project is een groot gedeelte van dit proefschrift getuige. Van mei 1994 tot en met februari 1997 werd hij in tijdelijke dienst aangesteld als wetenschappelijk onderzoeker op de afdeling Keel , Neus-, en Oorheelkunde aan het Academisch Ziekenhuis Nijmegen en achtereenvolgens gefinancierd door het KNO research fonds, het Heinsius Houbolt Fonds, nogmaals het KNO-research fonds, en de Hersenstichting Nederland. Tijdens deze periode deed hij neurofysiologisch onderzoek naar hersenpotentialen bij volwassenen en kinderen met een cochleair implantaat. Vanaf maart 1997 is hij werkzaam als medisch psycholoog aan het Kinderaudiologisch Centrum van het Academisch Ziekenhuis Nijmegen

*Stellingen behorende bij het proefschrift van Paul Groenen Nijmegen, 3 december 1997*

# CENTRAL AUDITORY PROCESSING DISORDERS

*A Psycholinguistic Approach*

*1* Spraakdiscriminatie-problemen in kinderen met ontwikkelingsdyslexie kunnen niet worden teruggevoerd op een ontwikkelingsachterstand maar zijn het gevolg van een functionele afwijking van het auditieve analyse-systeem. *(dit proefschrift)*

*2* Kinderen die herhaaldelijk otitis media met effusie hebben gehad in de peuterjaren hebben op latere leeftijd spraakperceptieproblemen op auditief en fonetisch gebied die ongeveer even groot zijn als die van kinderen met een algemene taalachterstand. *(dit proefschrift)*

*3* De aard van de auditieve spraakwaarnemingsproblemen ten aanzien van consonanten bij kinderen met een verbale ontwikkelingsdyspraxie ondersteunen de idee dat verbale ontwikkelingsdyspraxie een stoornis is van senso-motorische aard. *(dit proefschrift)*

*4* Kinderen met spraakproblemen van dyspractische aard hebben problemen met zowel de productie als de perceptie van klinkers. *(dit proefschrift)*

*5* Dragers van een cochleair implantaat zijn het levende voorbeeld van de enorme neuroplasticiteit van het centraal auditieve systeem. *(dit proefschrift)*

*6* De interpretatie en typering van centraal auditieve symptomen zijn in belangrijke mate afhankelijk van de manier waarop de redundantie van het aangeboden spraakmateriaal is gereduceerd. *(dit proefschrift)*

*7* Hierarchisch gestructureerde spraakperceptie modellen hebben een beperkte klinische waarde voor de diagnose van centraal auditieve stoornissen bij kinderen met primaire en secundaire spraak- en taalproblemen. *(dit proefschrift)*

*8* Centraal auditieve stoornissen behoeven naast een aanpak op het gebied van de audiologie en de keel-neus-oorheelkunde een aanpak die psycholinguïstische aspecten benadrukt.

*9* Het gebrek aan gestandardiseerde en genormeerde Nederlandstalige centraal auditieve tests werkt foutieve diagnose en behandeling van taal- en spraakproblemen in de hand.

*10* Er bestaat een schrijnende discrepantie tussen hetgeen de experimenteel psycholoog graag wil onderzoeken op medisch gebied en hetgeen de medicus onderzocht wil hebben door de experimenteel psycholoog.

*11* Een Freudiaanse verspreking is regelmatig een Freudiaanse verluistering.

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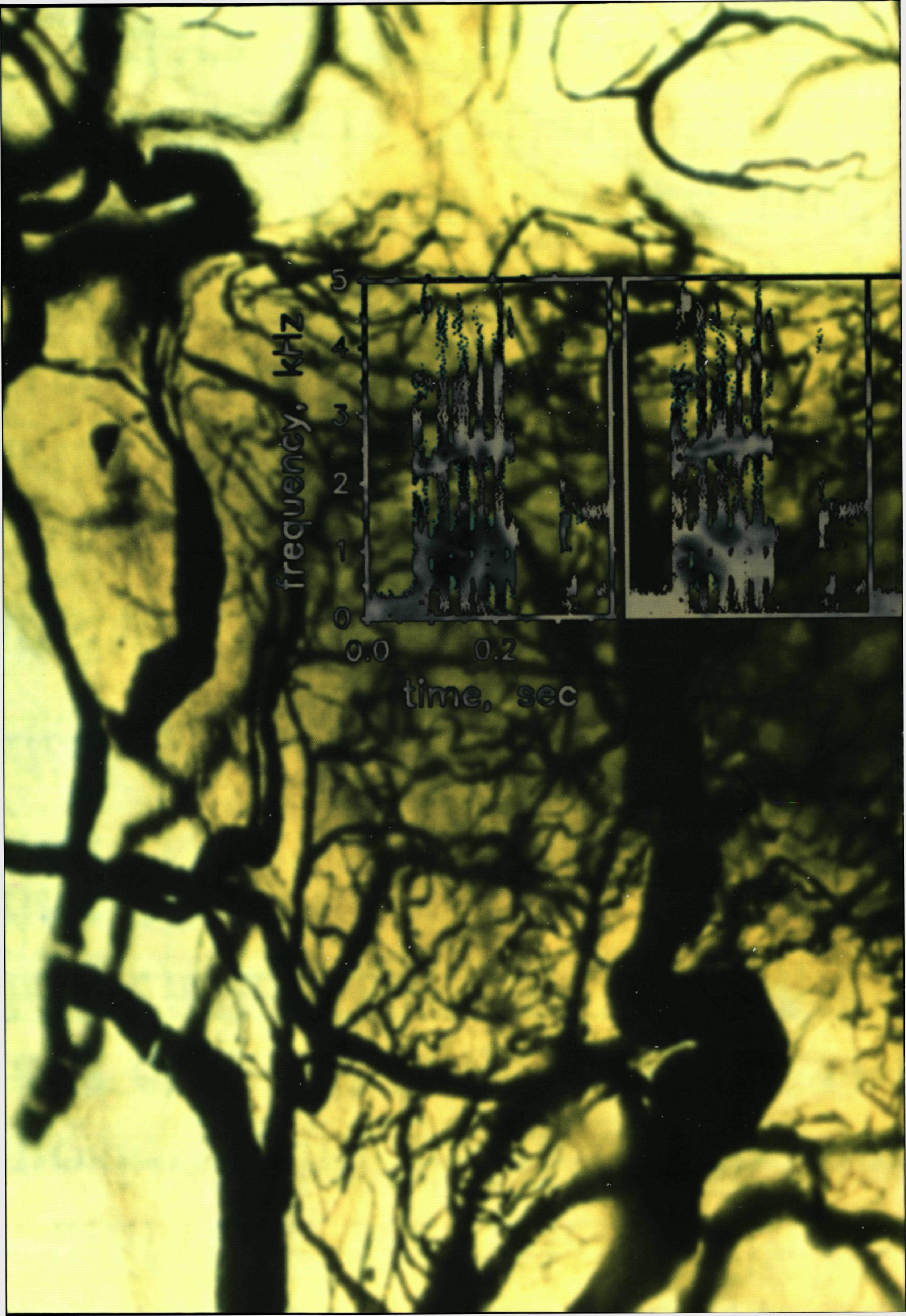
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